THE PERMEABILITIES OF AN ELASTOMER, A LOW-DENSITY EPOXY AND A LOW-DENSITY PHENOLIC-NYLON CHAR

Final Report

to

National Aeronautics and Space Administration
Hampton, Virginia

Contract NAS 1-5448
Task Order 6

Southern Research Institute
Birmingham, Alabama
8561-1728-6-IV
June 30, 1967

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ABSTRACT

The permeabilities of an elastomer, a low-density epoxy and a low-density phenolic-nylon ablation char were measured at room temperature for helium and nitrogen as separate permeating gases. The permeabilities were determined in terms of the viscous flow coefficient (reciprocal of Darcy's constant) and the inertial flow coefficient. The permeability of the char was evaluated as a function of temperature from room temperature to 810°K (1000°F) and as a function of direction within the char. The results indicate that the flow resistance of the char decreases with increasing temperature. Some directional effects were observed, but the results were not strongly conclusive.

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INTRODUCTION

This is the final report under Task Order 6 of Contract NAS 1-5448 for a project to determine the permeabilities of an elastomer, a low-density epoxy and a low-density phenolic-nylon char. Permeabilities of the elastomer, the low-density epoxy and the char parallel to the charring direction were measured at room temperature using both helium and nitrogen as the permeating gases. The permeability of the phenolic-nylon char perpendicular to the charring direction was measured from room temperature to 1000°F using both helium and nitrogen as the permeating gases.

SPECIMEN MATERIAL

The materials which were evaluated are discussed in the following paragraphs.

Elastomer

This material was a filled silicone resin. It contained some phenolic microballoons and some quartz particles. It was received as a disc about 7.6 cm in diameter by 0.951 cm thick.

Low-Density Epoxy

This material consisted of a fiber honeycomb filled with a low-density epoxy. The epoxy was blown into the honeycomb structure. A picture of this material is shown in Figure 1. The material was supplied as a disc about 7.6 cm in diameter by 2.9 cm thick. On one surface of the disc the epoxy had not completely filled the honeycomb and voids were left between the honeycomb structure and the epoxy. Specimens were removed from the opposite side as designated by the NASA Langley Research Center.

Phenolic-Nylon Char

This material was supplied by the NASA Langley Research Center in the form of charred discs. Three discs were received which were about 7.6 cm in diameter by 2.9 cm thick. They contained numerous striations (cracks) parallel to the charring direction and seemed to be striated worse than other discs charred by the NASA Langley Research Center. Undoubtedly, this severe striating was a result of charring to such a large depth, 2.9 cm. Prior chars were limited to a thickness of about 1.27 cm.

The bulk densities of two specimens were measured. These specimens were impregnated with polyalphamethylstyrene, machined to a cylindrical shape and then baked out. The weight and dimensions of the specimens were measured and the bulk density was calculated. The values obtained were 0.19 g/cc and 0.21 g/cc.

APPARATUS AND PROCEDURE

Two apparatuses were employed in making the measurements. The major difference in these apparatuses was in the manner in which the pressure measurements were made.

Room Temperature Apparatus

This apparatus is shown schematically in Figure 2. It consisted of a copper housing and a copper specimen holder. An o-ring was used as a seal between the housing and the specimen holder. Gas was supplied to the specimen from a commercial gas cylinder. Static pressures were measured at the inlet and exit points to the housing. Flow rates were measured with either a bubble type flowmeter, a variable area flowmeter or a wet test meter, the type of instrument used to measure the flow rate depending upon the magnitude of the flow.

The specimen, which was 2.54 cm in diameter by 1.77 cm thick, was mounted in the housing as shown in Figure 2. The specimen was mounted on a shoulder approximately 0.040 cm wide and 0.040 cm deep. On the upstream side the specimen holder was bored out to a diameter of 3.81 cm and the annulus between the specimen and the holder was filled with silicone rubber (Dow Corning RTV-731 Silastic). This silicone rubber had been employed successfully as a sealant in prior permeability measurements.

High Temperature Apparatus

This apparatus is shown schematically in Figure 3. A detail cutaway view of the housing and specimen holder is shown in Figure 4. The apparatus as shown in these figures was designed for operation to 1000°F (538°C). Gas was supplied to the apparatus from a commerical gas cylinder. The volumetric flow rate was measured with a variable area flowmeter. The inlet pressure to the flowmeter was read with a mercury filled U-tube manometer. This pressure measurement was used to correct the indicated flowmeter reading to the volumetric flow rate at standard pressure. Between the flowmeter and the specimen housing the gas passed through a preheater section. This consisted of thin-walled stainless steel tubing which was resistively heated using low-voltage, and high current. Power was supplied from a 25kW step-down transformer, the input of which was regulated by a 220 v Powerstat. The gas then passed through the specimen and was exhausted to the atmosphere.

The pressures upstream and downstream of the specimen where measured with total pressure probes. These pressure monitors were connected to U-tube manometers such that the manometers read the pressure difference across the specimen and the gage pressure on the downstream side of the specimen.

Temperatures were measured with two chromel/alumel thermocouples. One thermocouple was mounted in the stainless steel specimen holder. The other thermocouple was used to monitor the temperature of the gas leaving the downstream side of the specimen. The exposed junction of the gas thermocouple was placed so that the hot gas leaving the specimen impinged directly upon it.

Knife edges were machined on the faces of the housing and specimen holder. A copper gasket was used between these knife edges to provide a leaktight seal.

The specimen was mounted in a stainless steel housing as shown in Figure 4. The specimen rested in a recess approximately 0.040 cm wide by 0.080 cm deep. Above this recess the holder was bored out to a diameter of 3.81 cm. The specimens used for the measurements on the low-density epoxy were 2.54 cm in diameter by 1.27 cm thick. The specimens used for the measurements on the phenolic-nylon char were 1.59 cm in diameter by 0.95 cm thick. The holder was originally designed to accommodate a 2.54 cm diameter specimen. It was modified to accommodate the char specimens by welding a thin stainless steel disc in the bottom of the housing. The disc was machined to accommodate the smaller specimen diameter. The annulus between the specimen and the housing was filled with a sealing compound. A silicone rubber (Dow Corning RTV-731 Silastic) was used as the sealing compound for the room temperature measurements on the low-density epoxy. For the high temperature runs on the phenolic-nylon char, Sauereisen 31 cement was used as a sealant. Both of these sealing compounds had been used successfully on prior evaluations. A stainless steel washer was mounted on the exposed surface of the Sauereisen cement while it was still wet. This washer reduced the exposed area of the cement and served as a secondary seal.

The procedure for setting up the specimen using the Sauereisen cement was as follows. The annulus was filled about $\frac{3}{4}$ full with a fairly dry mix of the cement and then cured for about four hours at 250°F (121°C). Next a wet wash was applied and the washer was placed on top. The assembly was then cured for about four hours at 700°F (371°C). This last cure also served to break the polyalphamethylstyrene impregnant in the phenolic-nylon char ~~specimens down into a monomer and allow it to leave the specimen as a gas.~~ Once the impregnant is broken down into a monomer it cannot recondense on the specimen.

Procedure

Ambient Temperature Runs - The procedure in making the runs at ambient temperature was as follows: When the wet test meter was used, the system was purged for about 30 minutes to remove residual gases from the meter. The pressure regulator was adjusted to give the desired pressure difference across the specimen. Several minutes were allowed for the system to stabilize. Then the measurements were made.

Elevated Temperature Runs - The procedure in making the runs at elevated temperatures was as follows: The housing was brought up to temperature with no gas flow through the apparatus. After the housing temperature had stabilized, the gas flow was turned on and the pressure regulator was set to give the desired pressure drop across the specimen. The gas preheater was then turned on and the input power was increased until the gas reached the same temperature as the housing. At least two data points were taken at each pressure level to monitor that the two temperatures were in equilibrium and to reduce the risk of obtaining spurious readings.

General

During the runs the following data were recorded:

1. Atmospheric pressure (obtained from U.S. Weather Station)
2. Differential pressure across specimen
3. Downstream gage pressure

4. Pressure at flow instrument (at inlet to wet test meter or flowmeter; when flowmeter was used on the downstream side of housing no readings were taken because of the small pressure drop through the flowmeter venting to atmosphere).
5. Flowmeter readings
6. Housing temperature (for elevated temperature measurements only)
7. Gas temperature (for elevated temperature measurements only)
8. Temperature at wet test meter (when used)

All flowmeter readings were converted to the volumetric flow rate at standard pressure. All runs were made in both nitrogen and helium.

DATA CORRELATION

Theory

Greenberg and Weger[1*] concluded from a review of some of the literature on permeability that most of the data could be correlated with an equation of the type:

$$- \frac{dP}{dx} = \alpha \mu V + \beta \rho V^{n} \qquad (1)$$

where

$\frac{dP}{dx}$ = pressure gradient in the direction of flow

α = viscous flow coefficient (reciprocal of Darcy's constant, k)

V = instantaneous gas velocity

β = inertial flow coefficient

ρ = instantaneous gas density

μ = absolute viscosity

*See References listed at end of report.

and where n is some number between 1 and 2.

Carman[2] selected the value of n as 2 to account for turbulent flow. Greenberg and Weger[1] also state that correlations of the data of Cornell and Katz indicate that the value of n should be 2 to account for inertial flow through consolidated media.

In equation (1) the first term on the right hand side represents the resistance due to viscous flow. The second term on the right hand side represents the resistance due to inertial flow. Inertial flow results from turbulence induced by the tortuous path the gas must follow through the porous material and also by high velocities. Both of these phenomena depend upon the kinetic energy of the fluid per unit volume, ρV^2. Thus in developing equation (1) it was assumed that the expression for the inertial resistance could be superimposed upon the expression for the viscous resistance.

Under steady state conditions the mass velocity of gas (for one-dimensional flow) through a porous media must be constant. By letting $\rho V = G$ and $n = 2$, equation (1) becomes

$$-\rho \frac{dP}{dx} = \alpha\mu G + \beta G^2 \qquad (2)$$

where G = mass velocity

Now, for an ideal gas

$$\rho = \frac{PM}{RT} \qquad (3)$$

where

P = absolute pressure

M = molecular weight of gas

R = universal gas constant

T = absolute temperature

Substituting equation (3) into equation (2) and rearranging yields

$$-\frac{PM}{RT\mu G}\frac{dP}{dx} = \alpha + \frac{\beta G}{\mu} \tag{4}$$

or

$$-\frac{M}{RT\mu G}\int_{P_1}^{P_2} PdP = \left(\alpha + \frac{\beta G}{\mu}\right)\int_0^L dx$$

Integrating and rearranging equation (4) yields

$$\frac{MP_m \Delta P}{LRT\mu G} = \alpha + \beta\left(\frac{G}{\mu}\right) \tag{5}$$

where

$P_m = \frac{1}{2}(P_1 + P_2)$ = mean specimen pressure

$\Delta P = (P_1 - P_2)$ = differential pressure

L = thickness of specimen

Since G is a constant one may write

$$G = \frac{Q_{STP}\,\rho_{STP}}{A} \tag{6}$$

where

Q_{STP} = volumetric flow rate at standard conditions

ρ_{STP} = gas density at standard conditions

A = total cross section of porous media normal to flow

Standard conditions are defined as 14.7 psia (1.013×10^5 n/m^2) and 70°F (294.3°K).

Note that because of the way equation (6) is written G represents the "apparent" mass velocity since the total cross-sectional area, A, was used.

Now, note from equation (5) that a plot of $MP_m \Delta P/LRT\mu G$ versus G/μ should be linear. The slope of the curve will represent the inertial coefficient, β, and the intecept will be α (the reciprocal of Darcy's constant, k). Further note that if β is equal to zero, equation (5) reduces to Darcy's Law. That is, if $MP_m \Delta P/LRT\mu G$ is constant for all values of G/μ, the flow is purely viscous and Darcy's Law applies. For the data presented in this report it was found that the parameter $MP_m \Delta P/LRT\mu G$ was not constant and that the data could be correlated by using equation (5).

In equation (5) α is supposed to be a true constant and β may vary with flow rate. However, β generally does not vary rapidly with flow rate and its variation may usually be neglected[2]. Greenberg and Weger[1] have shown that α may vary with temperature while β remains constant. Both α and β may vary with temperature but can be considered constant for a given temperature. Both coefficients are functions of the structure of the porous material.

Data Reduction

The dependent and independent variables in equation (5) were calculated for each data point. Then a plot of $MP_m \Delta P/LRT\mu G$ versus G/μ was made. Such a presentation is known as a Cornell and Katz plot. A straight line was drawn through the points thus plotted and the viscous and inertial coefficients were obtained from the intercept and slope of the curve, respectively. Thus, for each specimen evaluated one viscous and one inertial coefficient were calculated at a given temperature level. Data were obtained over a sufficient range of the parameter (G/μ) to allow a good correlation and reduce the effects of spurious readings. The uncertainty in the reduced data was estimated to be $\pm$ 7 percent.

DATA AND RESULTS

Elastomer

The elastomer was impervious within the limits of our ability to monitor flow rates without modifications to the techniques employed. Specimens of the elastomer were mounted in the room temperature apparatus using a silicone rubber (Dow Corning RTV-731 Silastic) as a sealing compound. A pressure differential of 481×10^3 n/m^2 (70 psi) was imposed across the specimens. Under this differential pressure there was no observable flow through the specimen when a bubble type flowmeter was used and helium was the permeating gas. The bubble flowmeter can measure flow rates as low as 0.1 cm^3/sec.

Three specimens were fractured at a differential pressure of about 481×10^3 n/m^2 (70 psi). Two of these specimens were mounted using silastic as the sealing compound and the other was mounted using epoxy as a sealing compound. In all cases failure of the specimen occurred before any flow could be observed on the bubble type flowmeter.

Pictures of a failed specimen are shown in Figure 5.

Low-Density Epoxy

A picture of this material is shown in Figure 1. Four specimens of this material were evaluated at room temperature. Specimens 1, 2, and 4 were run using silastic as a sealing compound. Specimen 3 was evaluated using epoxy as a sealing compound. The epoxy proved to be a poor sealant. A visual inspection of the specimen mounted in epoxy showed that the epoxy had penetrated into the pores of the specimen thus reducing the cross-sectional area. For this reason the data obtained for Specimen 3 were not presented.

The high temperature apparatus was used to make the measurements on Specimens 1 and 2. The equipment was modified from the arrangement shown in Figure 3 so that the flow rate was measured on the downstream side of the housing. The room temperature apparatus was used to make the measurements on Specimen 4.

The data for Specimen 1 are presented in Table 1. The data covered a range of differential pressures from 5 in. Hg to 30 in. Hg. Shown in Figure 6 is a plot of the mean flow rate through this specimen versus the differential pressure.

Darcy's Law for viscous flow may be written

$$Q_m = \frac{kA}{L\mu} \Delta P \qquad (7)$$

where

$$Q_m = Q_{STP} \frac{\rho_{STP}}{\rho_m} = \text{mean flow rate through specimen}$$

and where

ρ_{STP} = gas density at standard conditions of temperature and pressure

Q_{STP} = flow rate through specimen at standard conditions of temperature and pressure

Inspection of equation (7) reveals that for purely viscous flow the mean flow rate should be linear with pressure and that the slope of the curve is proportional to k/μ. The viscosities of helium and nitrogen at ambient temperature are 1.98×10^{-2} centipoise and 1.756×10^{-2} centipoise, respectively. Thus, if the flow is purely viscous the nitrogen flow rate should be approximately 13 percent higher than the helium flow rate since the viscosity of nitrogen is 13 percent lower and Darcy's constant should be the same for both gases. Note in Figure 6 that the flow rate was nearly the same for both gases up to 15 in. Hg and that above this differential pressure the flow rate of helium was higher. There was a slight trend toward purely viscous flow at the lower flow rates. This led to the conclusion that inertial effects could not be neglected. Thus, equation (5) which included inertial effects was used to correlate the data. It should be noted that equation (5) also applies to viscous flow. A Cornell and Katz plot of the data for Specimen 1 is shown in Figure 7. The reduced data points all fell within about 6 percent of a straight line. The reciprocal of the intercept of the straight line is Darcy's constant, k. The value obtained for this parameter was 2.13×10^{-8}cm^2. The inertial coefficient, β, is the slope of the line. Its value was 2.58×10^4 cm^{-1}.

The data for Specimen 2 are presented in Table 2. These data covered a range of differential pressure from 5 in. Hg to 30 in. Hg. A Cornell and Katz plot of the data is presented in Figure 8. Darcy's constant, k, and the inertial coefficient reduced from Figure 8 were 2.39×10^{-8}cm^2 and 2.05×10^4 cm^{-1}, respectively.

The data for Specimen 4 are presented in Table 3. For this specimen data were obtained over a range of differential pressures from less than 1 in. H_2O to 30 in. Hg. The flow rate through the specimen is plotted versus the differential pressure in Figure 9 for a range of differential pressures from 0.3 to 1.0 in. H_2O. Note that even at these low differential pressures the flow does not appear to be purely viscous (the flow of nitrogen was not higher by an amount proportional to the difference in the viscosities of the two gases).

A Cornell and Katz plot of the data obtained on Specimen 4 is shown in Figure 10. From this plot Darcy's constant, k, and the inertial coefficient, β, were determined to be 2.26×10^{-8} cm^2 and 2.55×10^4 cm^{-1}, respectively.

The values obtained for Darcy's constant and the inertial flow coefficient for the three specimens are summarized in the table below.

Specimen	Darcy's Constant k (in 10^{-8}cm^2)	Inertial Flow Coefficient β (in 10^4cm^{-1})
Low-Density Epoxy Specimen 1	2.13	2.58
Low-Density Epoxy Specimen 2	2.39	2.05
Low-Density Epoxy Specimen 4	2.26	2.55
Average	2.26	2.39

There was a scatter of about 12 percent in the values for Darcy's constant and of about 22 percent in the values for the inertial flow coefficient. This scatter probably reflects differences in the bond between the epoxy and the honeycomb and differences in the amount of honeycomb in the specimens. Some of the flow occurs through the low-density epoxy filler, some through the fibrous honeycomb and some through any interstices between the two. The "apparent" permeability of the composite depends upon the relative amounts of each constituent and the permeabilities of these constituents. Undoubtedly, each of the samples did not contain the same percentage of honeycomb per unit of area. Thus, a variation between specimens was expected. The effects of each of the two constituents on the "apparent" permeability of the composite cannot be determined without separate measurements of the permeabilities of these constituents.

Low-Density Phenolic-Nylon Char

Parallel to the Charring Direction - The permeability of the char in the direction parallel to the charring direction was measured at room temperature. Two specimens were evaluated. One specimen was evaluated in the as-received condition and the other was impregnated with polyalphamethylstyrene so that a specimen could be machined.

The unimpregnated specimen was placed in the housing of the high temperature apparatus and a silicone rubber was used as a sealant. Steel washers were placed on the top and bottom of the specimen and bonded to the specimen with silicone rubber. The flow area for this specimen was defined as the area of the opening in the washer. The specimen actually had a larger area than this opening since a perfectly round specimen could not be machined from this grossly cracked material without impregnating it beforehand.

The impregnated specimens were filled with polyalphamethylstyrene so that a specimen could be machined to close tolerances. It should be noted that more impregnant had to be used for this material than for previous chars in order to hold the material together during machining. The machined specimen was partially mounted in Sauereisen cement and then cured at 250°F for about four hours. A final wet wash of the same cement was then applied in the annulus between the specimen and the housing and a stainless steel washer was set in the wet cement. The assembly was then baked out at 700°F for about four hours in order to cure the cement and remove the impregnant. Some surface spalling was noted as a result of bubbling of the impregnant before it reached a high enough temperature to gasify.

Pictures of the chars used for the measurements parallel to the charring direction are shown in Figure 11. Specimen 1 shown in the figure was unimpregnated, whereas, Specimen 2 was impregnated. Also shown in the figure is a sample of a phenolic-nylon char on which prior permeability measurements were made.[3]

The data obtained for the unimpregnated specimen (parallel to the charring direction) are presented in Tables 4 and 5 for Runs 1 and 2, respectively. A first run was made in nitrogen at the same time as the variable area flowmeters employed were being checked against a wet test meter. During these calibrations, after the permeability measurements were made, the differential pressure across the specimen reached values as high as 10 in. Hg. Subsequently, a second run was made on the same specimen. In the interim the specimen remained mounted in the housing. The data for the two runs were different. This may have resulted from changes in the specimen caused by the high differential pressures during the flowmeter calibrations. Cornell and Katz plots of the data for Runs 1 and 2 on Specimen 1 are presented in Figures 12 and 13, respectively. The inertial flow coefficients were 0.57×10^3 cm^{-1} and 0.38×10^3 cm^{-1} for the first and second runs, respectively. Darcy's constant changed only from 3.8×10^{-6} cm^2 to 3.7×10^{-6} cm^2 from one run to the next. One other possible explanation of the difference in values may be as follows: This specimen was sanded on one side in order to obtain parallel surfaces. The residue from the sanding filled the surfaces pores and cracks of the specimen. This residue was blown out of the cracks after the first run and may have caused the change in values.

Some permeability measurements on phenolic-nylon chars were reported in Reference 3. Those data were obtained on unimpregnated chars (a picture of this material is shown in Figure 11). Also, the char depth for the prior evaluations was only about 0.64 cm. Using equation (5) the prior data were correlated and are plotted in Figures 12 and 13 for a comparison with the current measurements. Note that the inertial flow coefficient, β, ranged from 0.42×10^3 cm^{-1} to 0.52×10^3 cm^{-1} for the two specimens used for the measurements in Reference 3. These values fell within the range of values obtained for Runs 1 and 2 on Specimen 1. Further note that Darcy's constant for the prior material was lower than the values obtained for Specimen 1. Note in Figure 11 that the prior material contained smaller cracks than the current material; hence, one would expect less flow through it and a lower value for Darcy's constant.

The data for Specimen 2, which was impregnated, are presented in Table 6. A Cornell and Katz plot of the data is shown in Figure 14. The inertial flow coefficient for this specimen was 0.33×10^3 cm^{-1} and Darcy's constant was 4.0×10^{-6}cm^2. The value for the inertial flow coefficient was 42 percent lower than that obtained for the first run on Specimen 1 (unimpregnated) and 13 percent lower than the value obtained for the second run. There was only about 5 percent difference in the values of Darcy's constant.

The results indicate that the value for Darcy's constant increases with increased char depth. More flow paths probably are opened as the char depth increases. For chars of 0.64 cm and 2.54 cm thickness, the values of Darcy's constant were 2.6×10^{-6}cm^2 and 3.8×10^{-6}cm^2, respectively. The inertial flow coefficient does not appear to be significantly affected by charring depth as the results were mixed.

More evaluations are needed to resolve the question of the effects of impregnation on the permeability. From this limited amount of data it appears that the impregnant opens up additional flow paths in the material. However, it is extremely difficult to obtain an unimpregnated specimen without introducing uncertainties in the measurements. Hence, the results are confounded.

Thus, at this point one can only say that the ranges of values of the coefficients for the thick char (2.54 cm) parallel to the charring direction are as follows:

$$\beta = 0.33 \times 10^3\ \mathrm{cm}^{-1} \text{ to } 0.57 \times 10^3\ \mathrm{cm}^{-1}$$

$$k \doteq 3.7 \times 10^{-6}\ \mathrm{cm}^2 \text{ to } 4.0 \times 10^{-6}\ \mathrm{cm}^2$$

Perpendicular to the Charring Direction - Duplicate measurements were made on the char from room temperature to 1000°F perpendicular to the charring direction. The specimens for these evaluations were impregnated and were built up in the manner described for the impregnated specimen used for the measurements parallel to the charring direction. Pictures of Specimen 3 are shown in Figure 15.

The data for Specimens 1 and 3 are shown in Tables 7 and 8, respectively. The values of the Cornell and Katz parameter are also given in the tables. The values used for the viscosities of helium and nitrogen in the calculations are shown in Figure 16. Cornell and Katz plots for the room temperature measurements are shown in Figures 17 and 18 for Specimens 1 and 3, respectively. Similar plots were made from the measurements at each temperature level above room temperature in order to obtain the coefficients as functions of temperature. The values obtained for the permeability coefficients are shown in Figure 19. Darcy's constant increased from $2.7 \times 10^{-6}\mathrm{cm}^2$ at room temperature to $4.1 \times 10^{-6}\ \mathrm{cm}^2$ at 1000°F. Note that the agreement between the two specimens was excellent. The inertial flow coefficient decreased from room temperature to 1000°F. Specimen 1 exhibited a decrease from $0.53 \times 10^3\ \mathrm{cm}^{-1}$ at room temperature to $0.43 \times 10^3\ \mathrm{cm}^{-1}$ at 1000°F. The decrease was from $0.53 \times 10^3\ \mathrm{cm}^{-1}$ at room temperature to $0.48 \times 10^3\ \mathrm{cm}^{-1}$ at 1000°F for Specimen 3. The values for the inertial flow coefficient of the two specimens agreed within 11 percent, which is considered good agreement for this material.

An inspection of equation (2) will reveal the significance of the changes in the coefficients. Note that if the coefficients α and β decrease, the flow corresponding to a given pressure drop increases, hence there is less flow resistance. Since Darcy's constant, k, is the reciprocal of the viscous flow coefficient, α, a decrease in flow resistance will be manifested by an increase in Darcy's constant. Thus the results of the measurement show that the flow resistance becomes less as the temperature is increased. The thermal expansion of the material as it is heated probably opens up the cracks, thus decreasing the flow resistance. The change did not seem to result from additional cracking of the material since room temperature data were obtained after the exposures to 1000°F and agreed well with the initial values (see Figures 17 and 18).

Summary of Phenolic-Nylon Char Results - Darcy's constant was lower in the direction perpendicular to the charring direction as its value was only $2.7 \times 10^{-6} cm^2$ at room temperature as compared to $3.7 \times 10^{-6} cm^2$ to $4.0 \times 10^{-6} cm^2$ parallel to the charring direction. The inertial flow coefficient, β, was higher in the direction perpendicular to the charring direction based on the results obtained for similarly prepared specimens (impregnated). At room temperature the value for the perpendicular direction was $0.53 \times 10^3 cm^{-1}$ as compared to $0.33 \times 10^3 cm^{-1}$ for the parallel direction. One would expect these results since the flowpath is more tortuous in the perpendicular direction and thus introduces more inertial resistance. It should be pointed out that these results could have been changed had not judicious care been used to select perpendicular specimens from the least cracked areas of the char blanks supplied. In some areas of the char blanks there were cracks which were at least 0.32 cm wide. Had a specimen been taken from these areas, its flow resistance would have been small.

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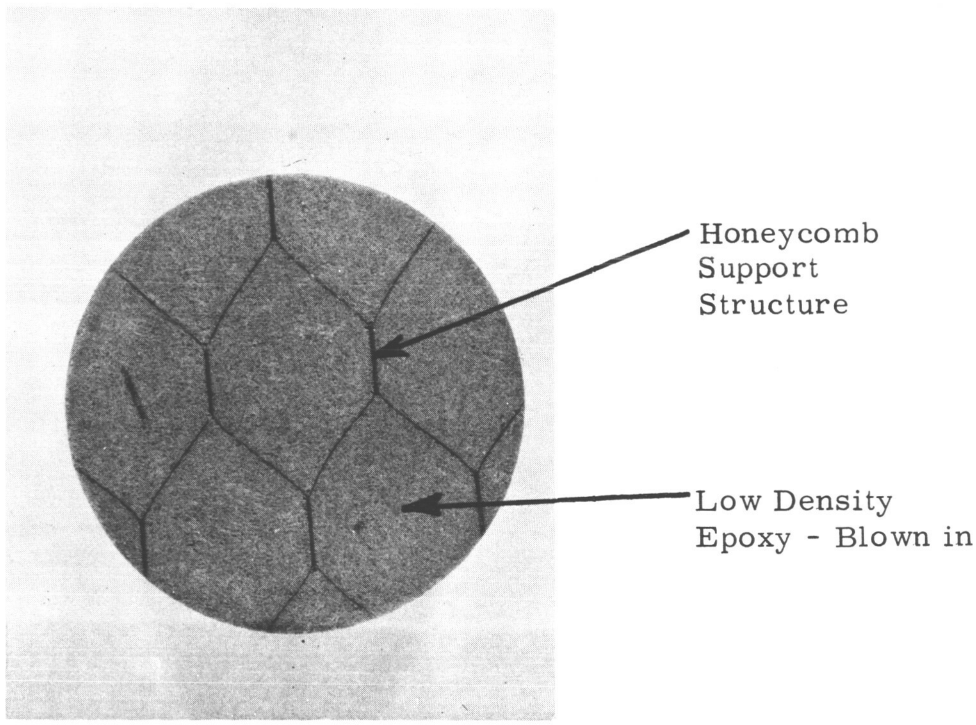


Figure 1. Picture of low-density epoxy

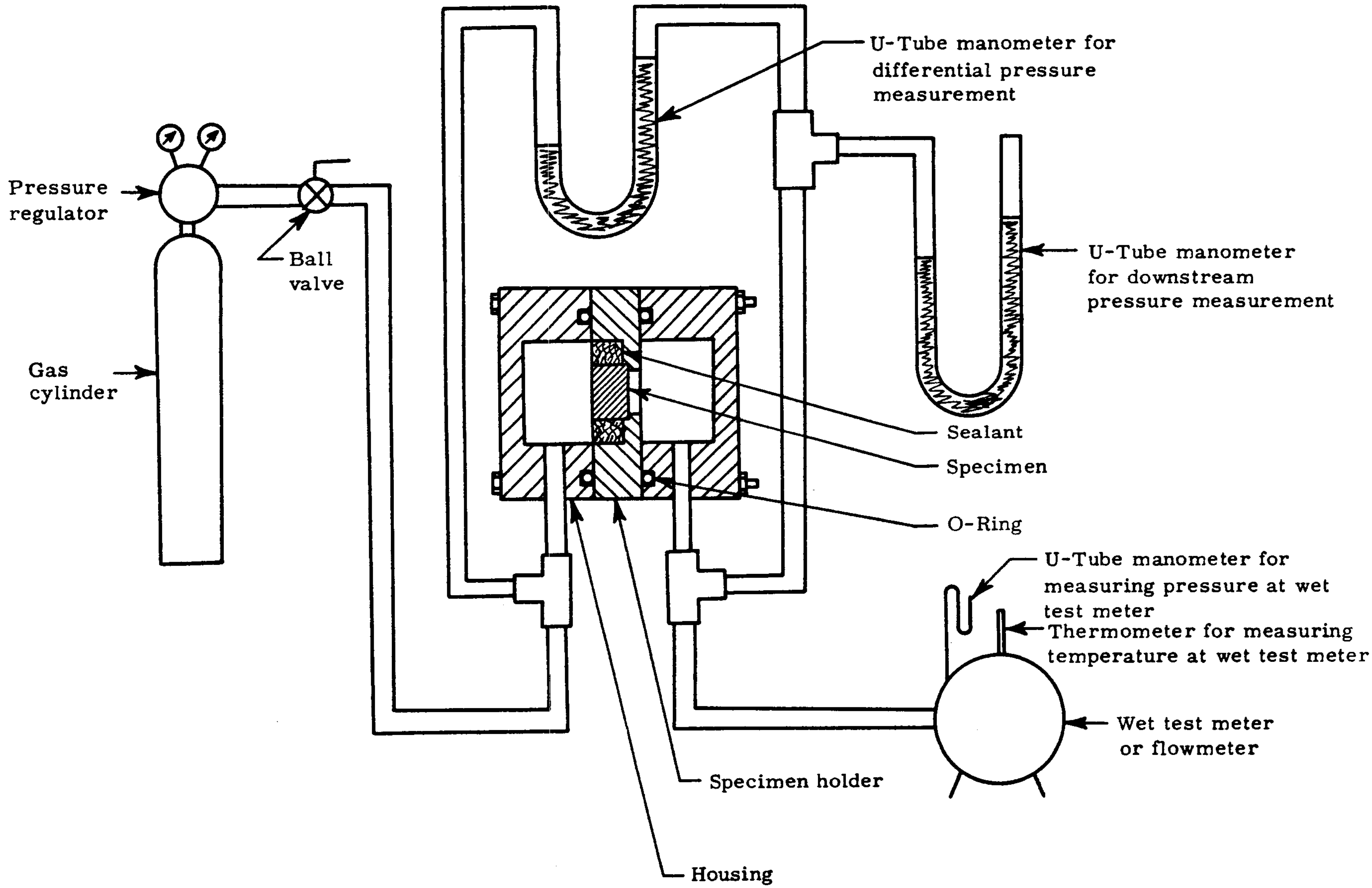


Figure 2. Permeability apparatus for room temperature permeability measurements

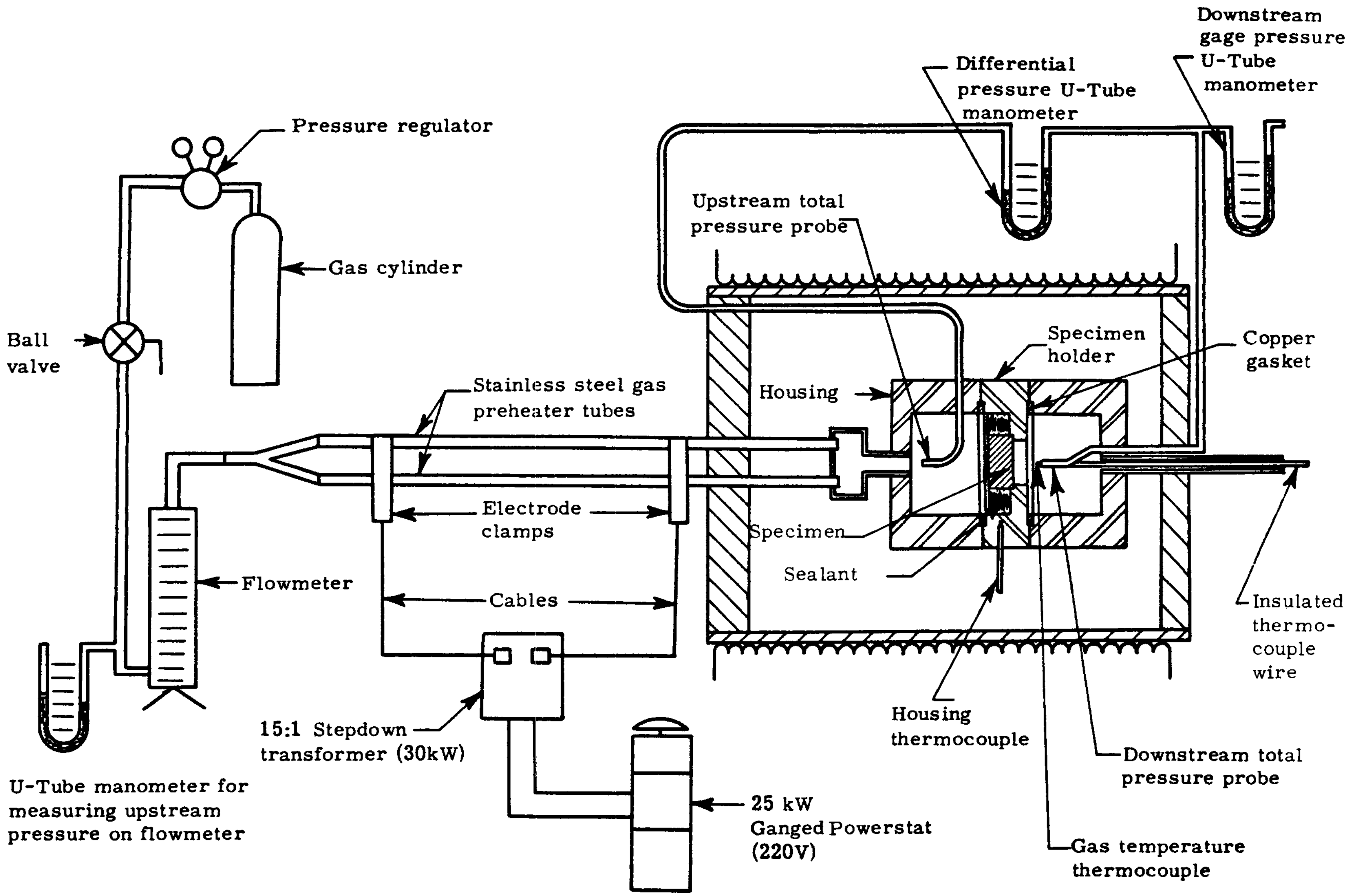


Figure 3. Permeability apparatus for measurements to 1000°F

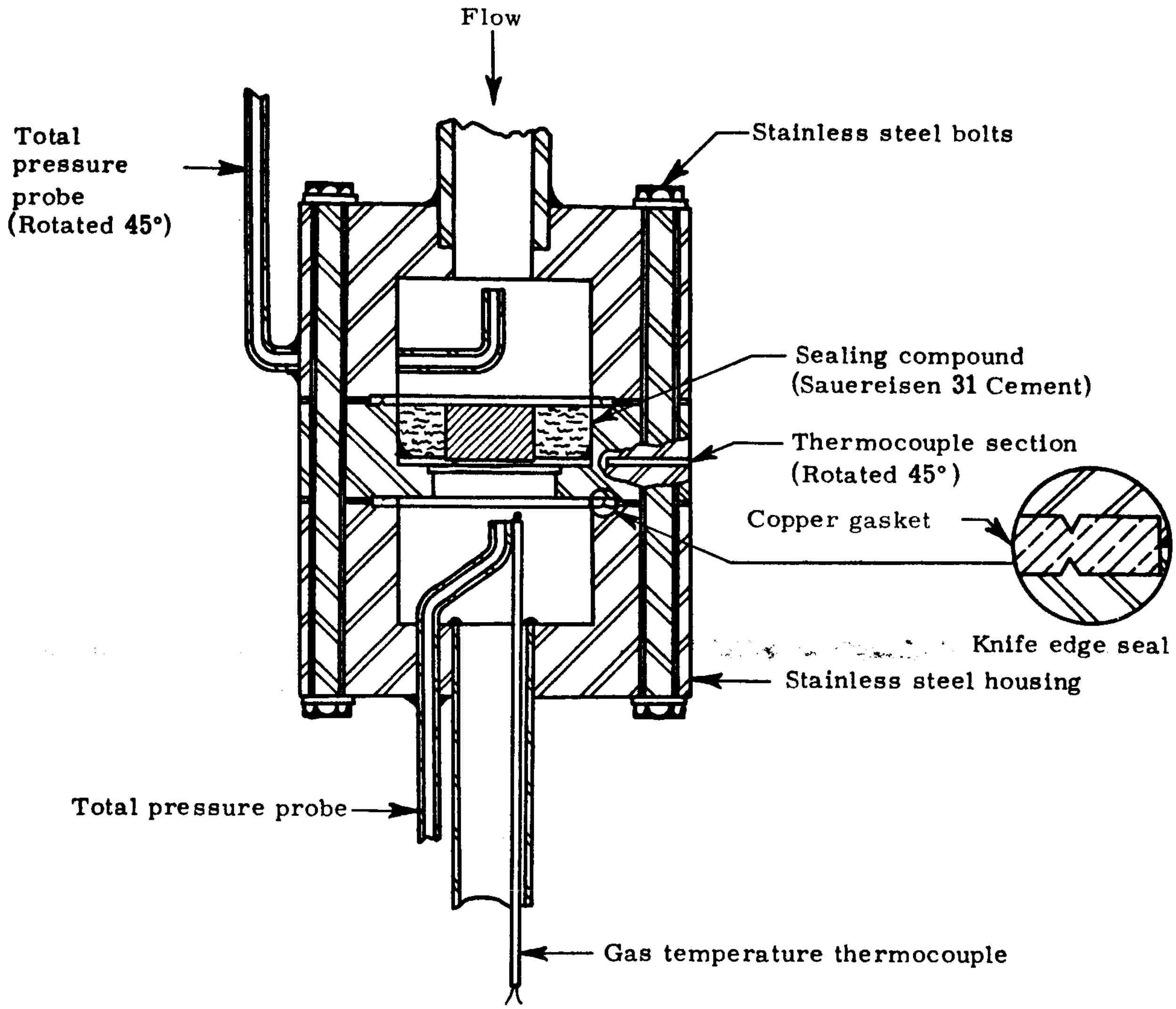
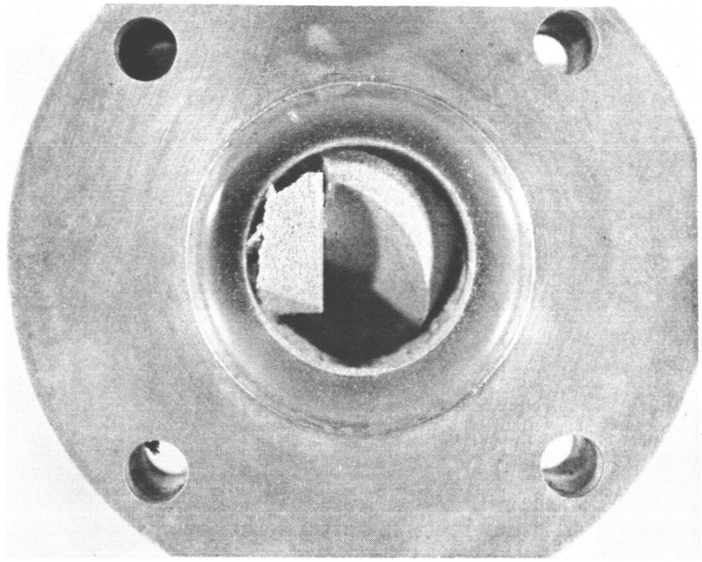


Figure 4. Details of specimen holder for high temperature permeability measurements



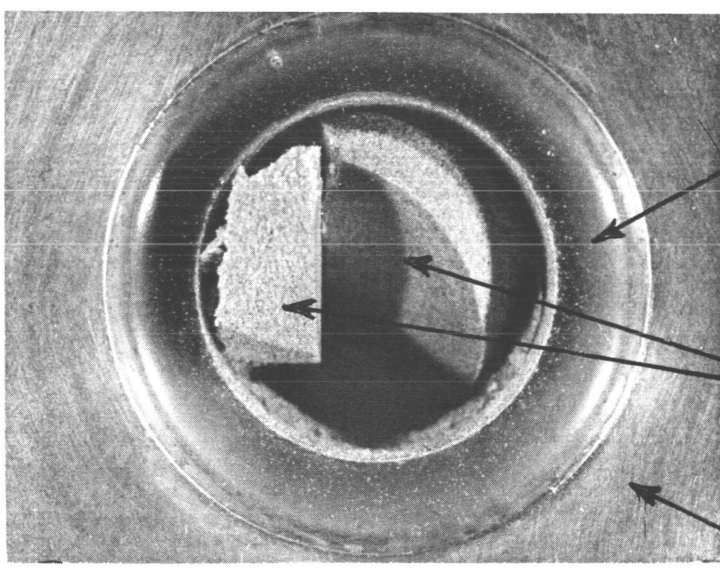


Figure 5. Pictures of an elastomer specimen which failed during a permeability evaluation

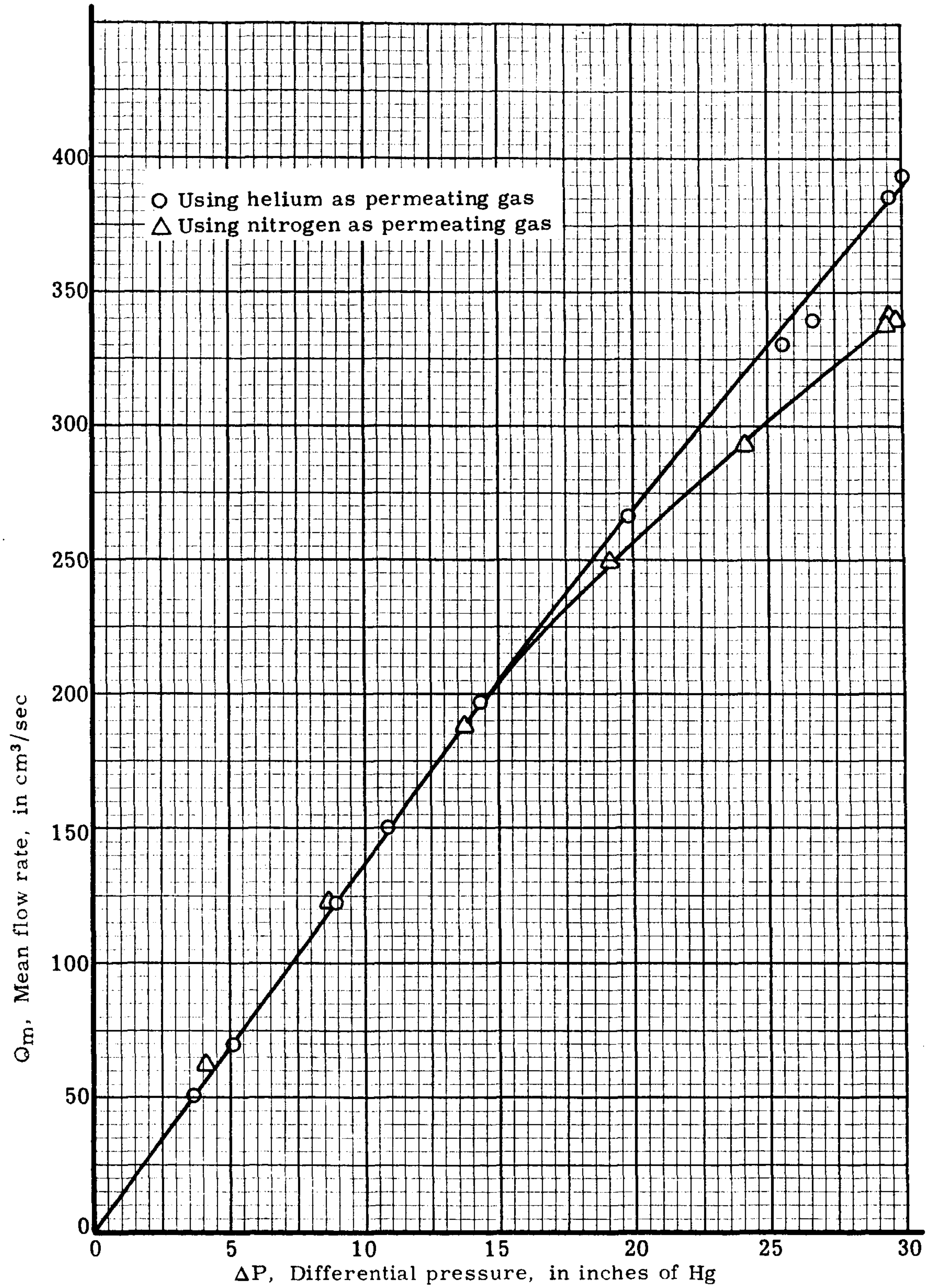


Figure 6. Mean flow rate versus differential pressure for low-density epoxy Specimen 1

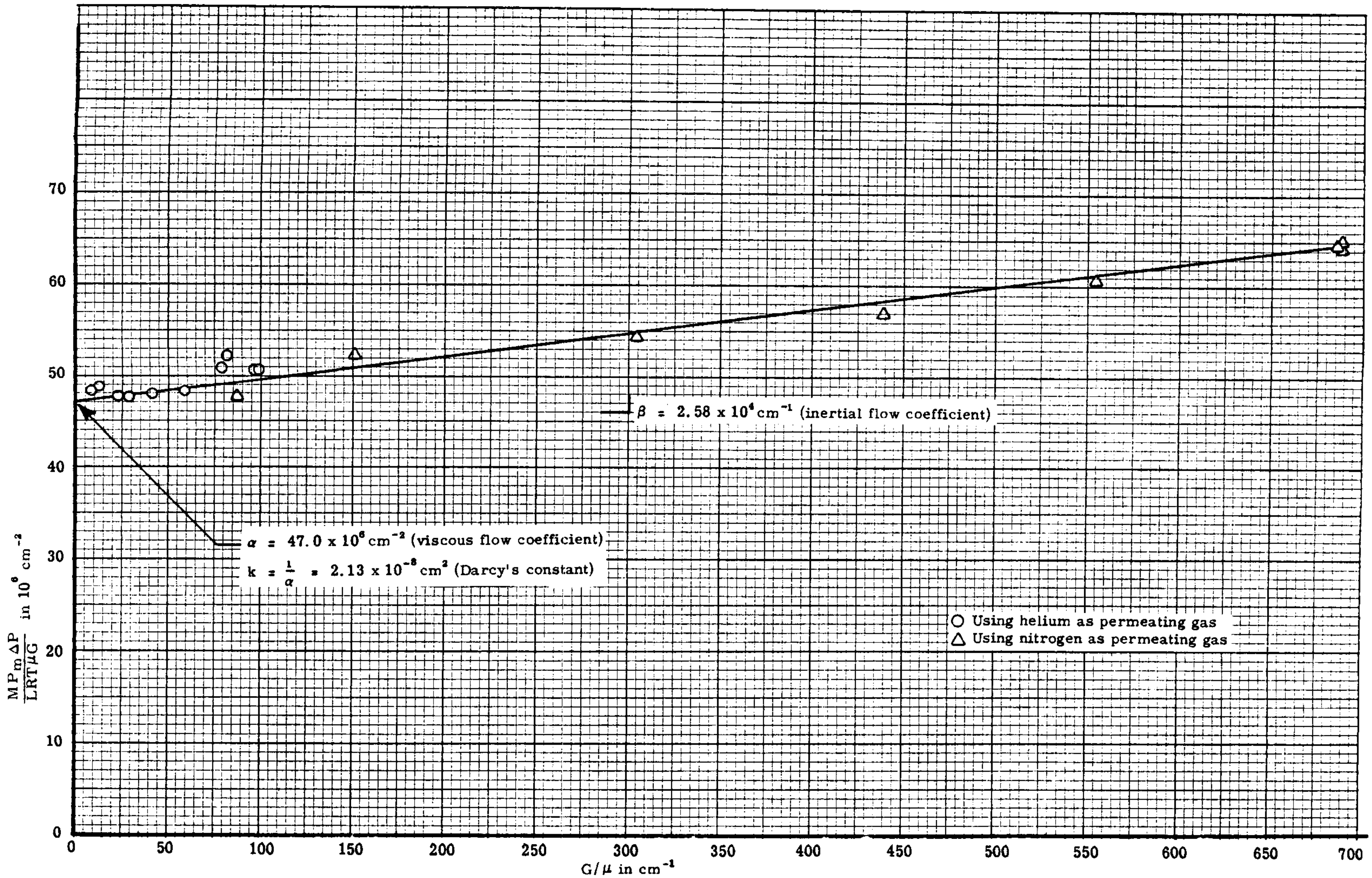


Figure 7. Cornell and Katz plot for low-density epoxy Specimen 1 at room temperature

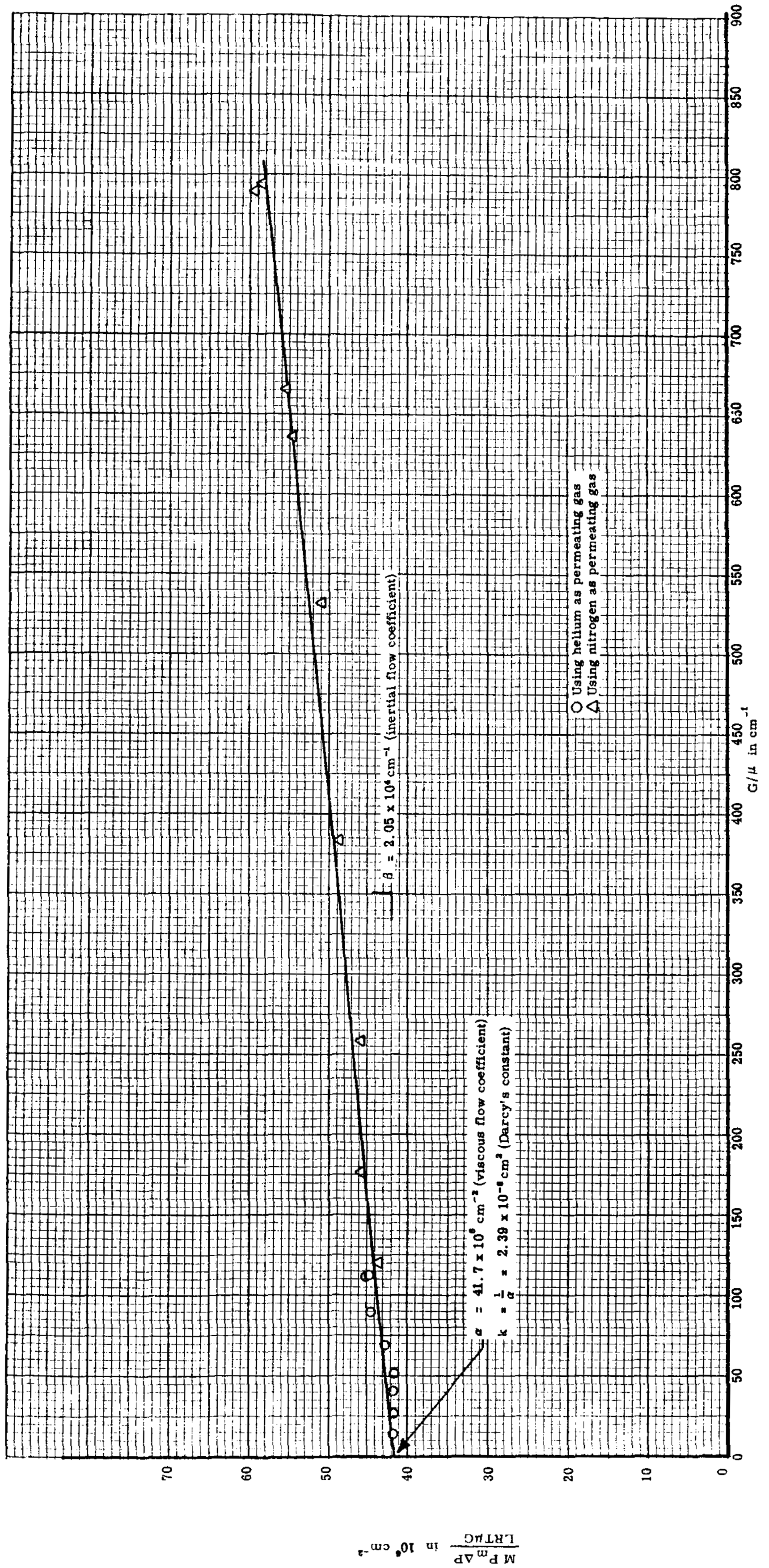


Figure 8. Cornell and Katz plot for low-density epoxy Specimen 2 at room temperature

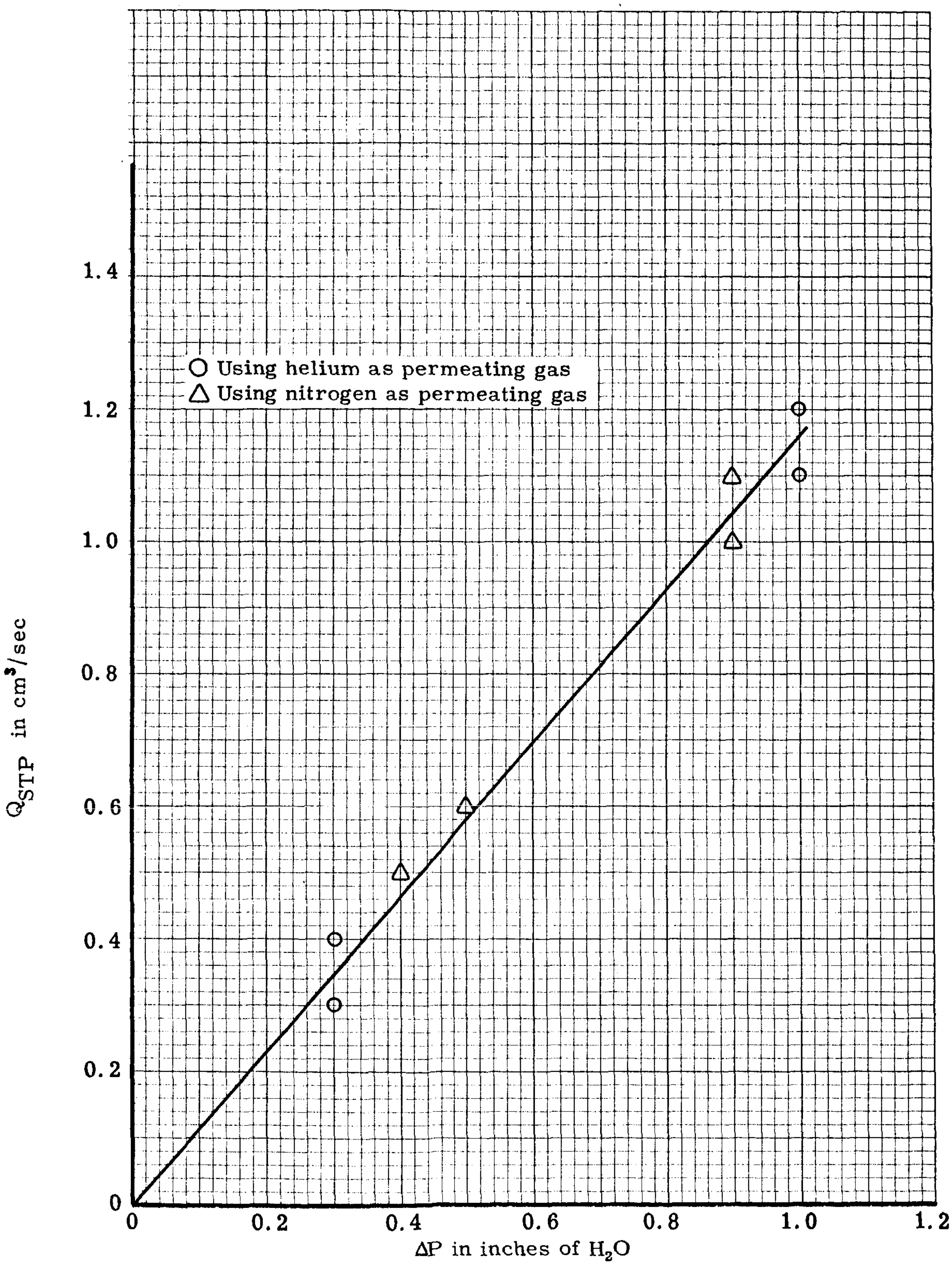


Figure 9. Flow rate versus differential pressure at low differential pressures for low-density epoxy Specimen 4 at room temperature

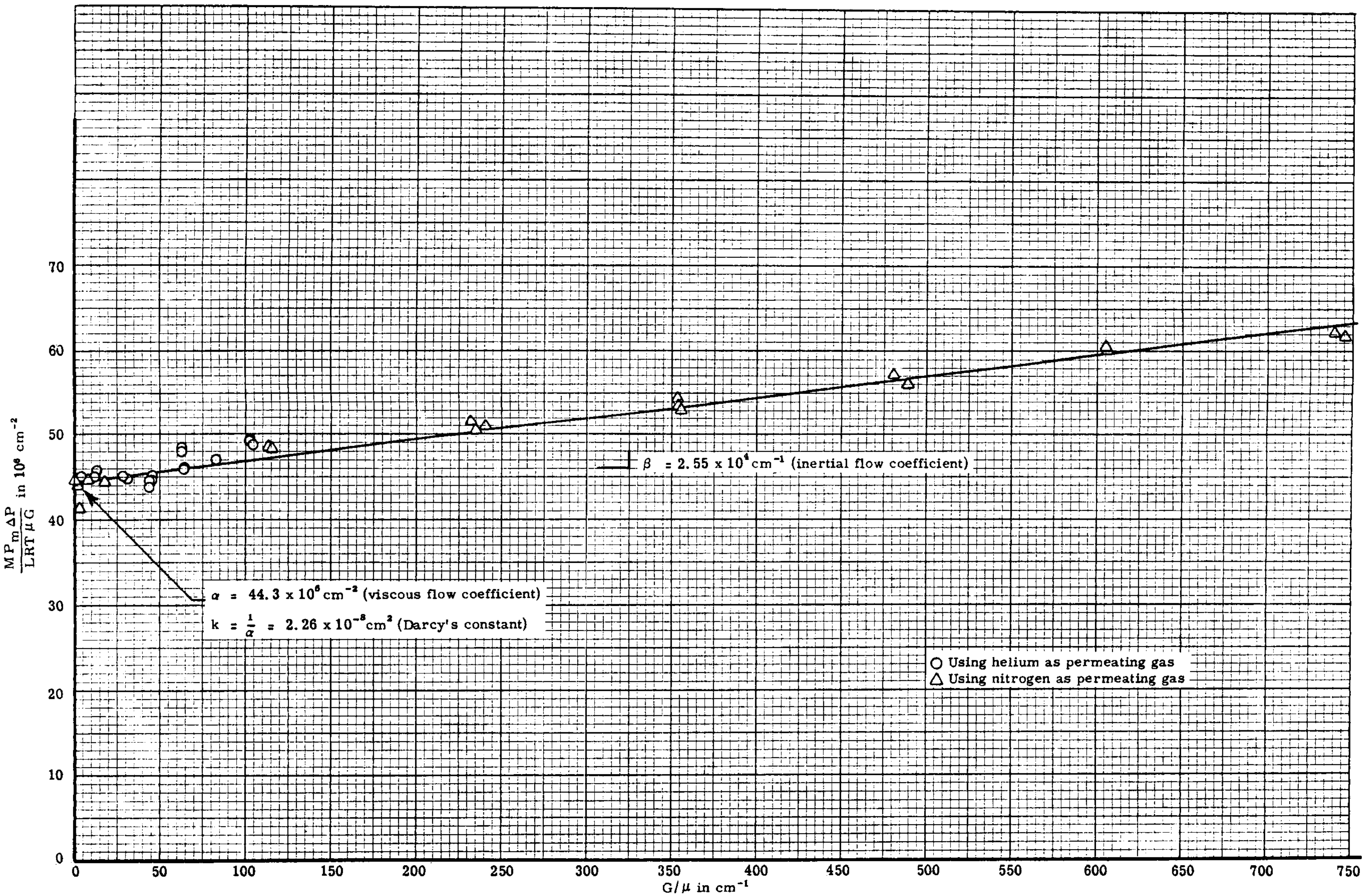
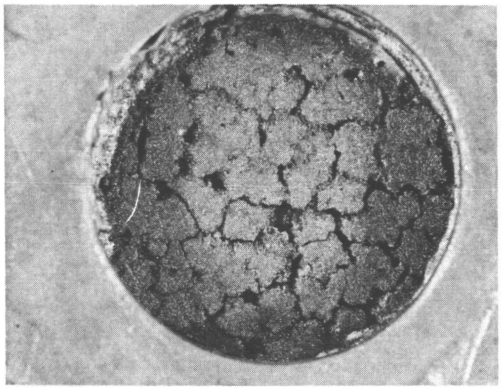
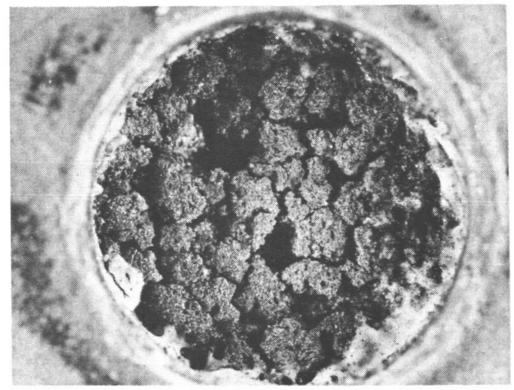


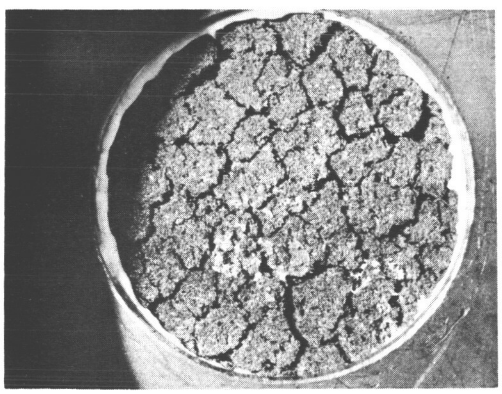
Figure 10. Cornell and Katz plot for low-density epoxy Specimen 4 at room temperature



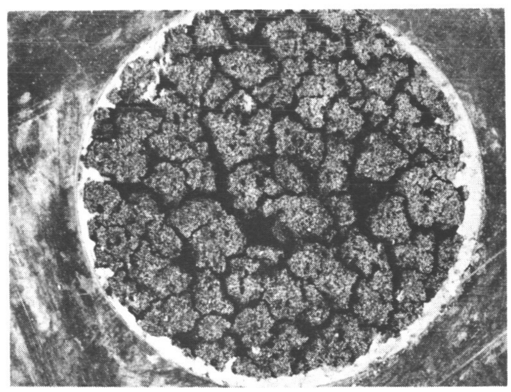
Specimen 1, Front Surface
(Unimpregnated)



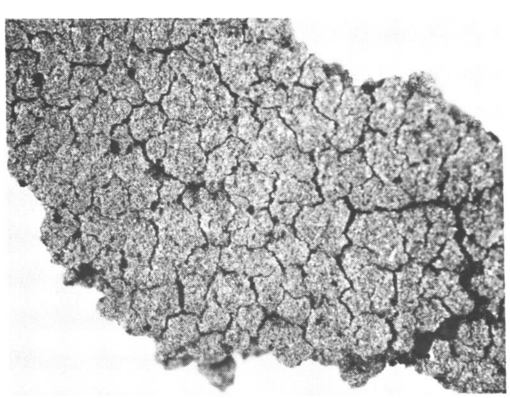
Specimen 1, Rear Surface
(Unimpregnated)



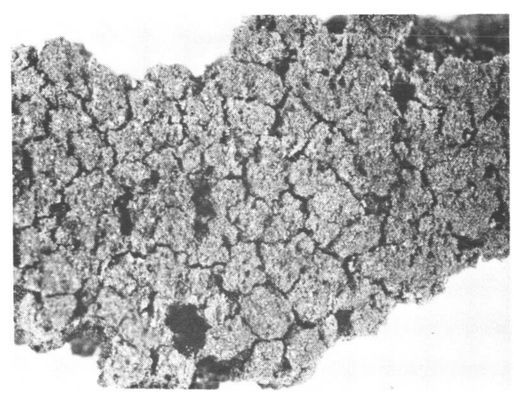
Specimen 2, Front Surface
(Impregnated)



Specimen 2, Rear Surface
(Impregnated)



Char Used for Measurements
Reported in Reference 3
Front Surface



Char Used for Measurements
Report in Reference 3
Rear Surface

Figure 11. Pictures of phenolic-nylon char used for measurements reported in Reference 3 and for measurements parallel to the charring direction

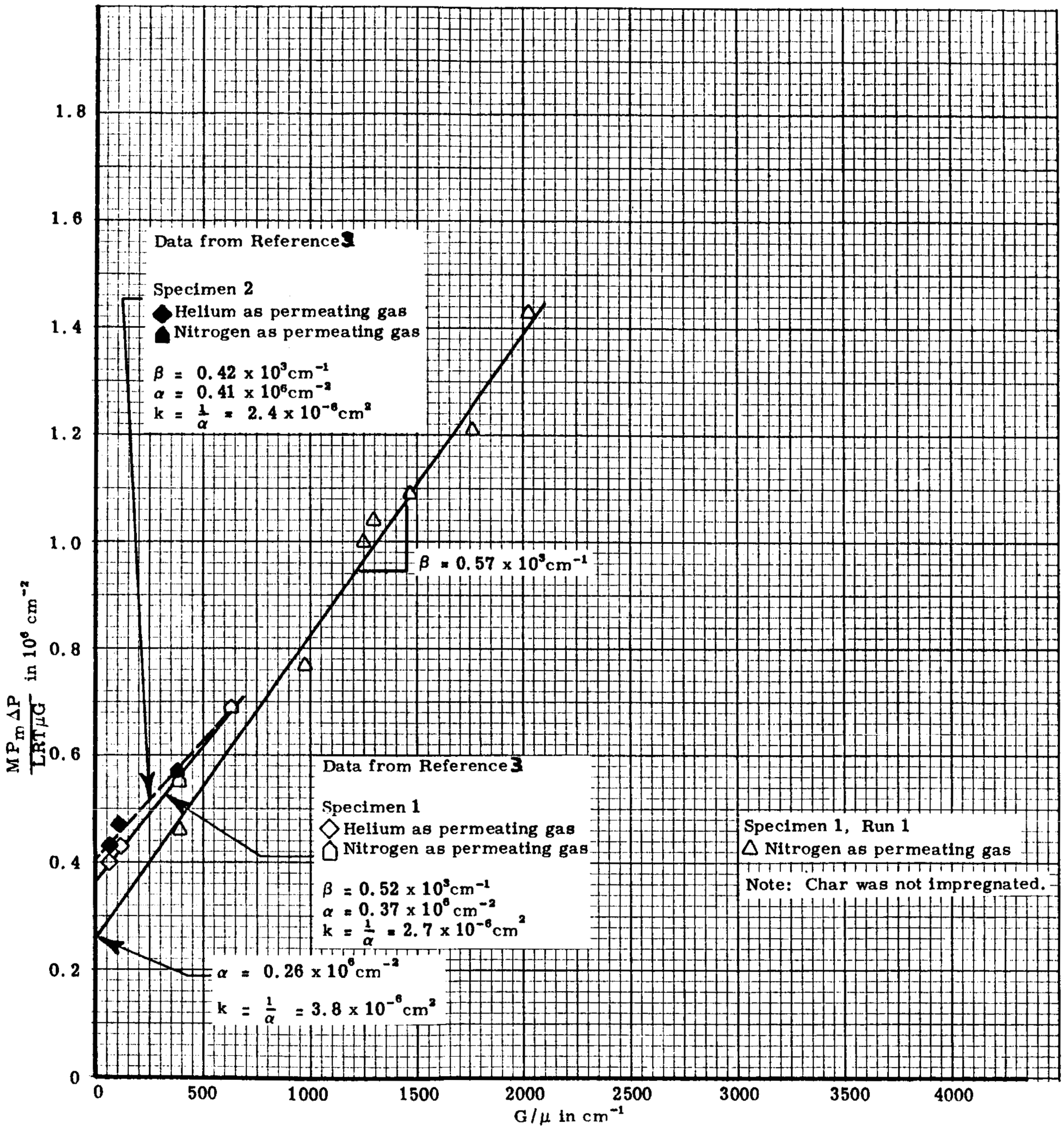


Figure 12. Cornell and Katz plot for low-density phenolic-nylon char parallel to the charring direction at room temperature

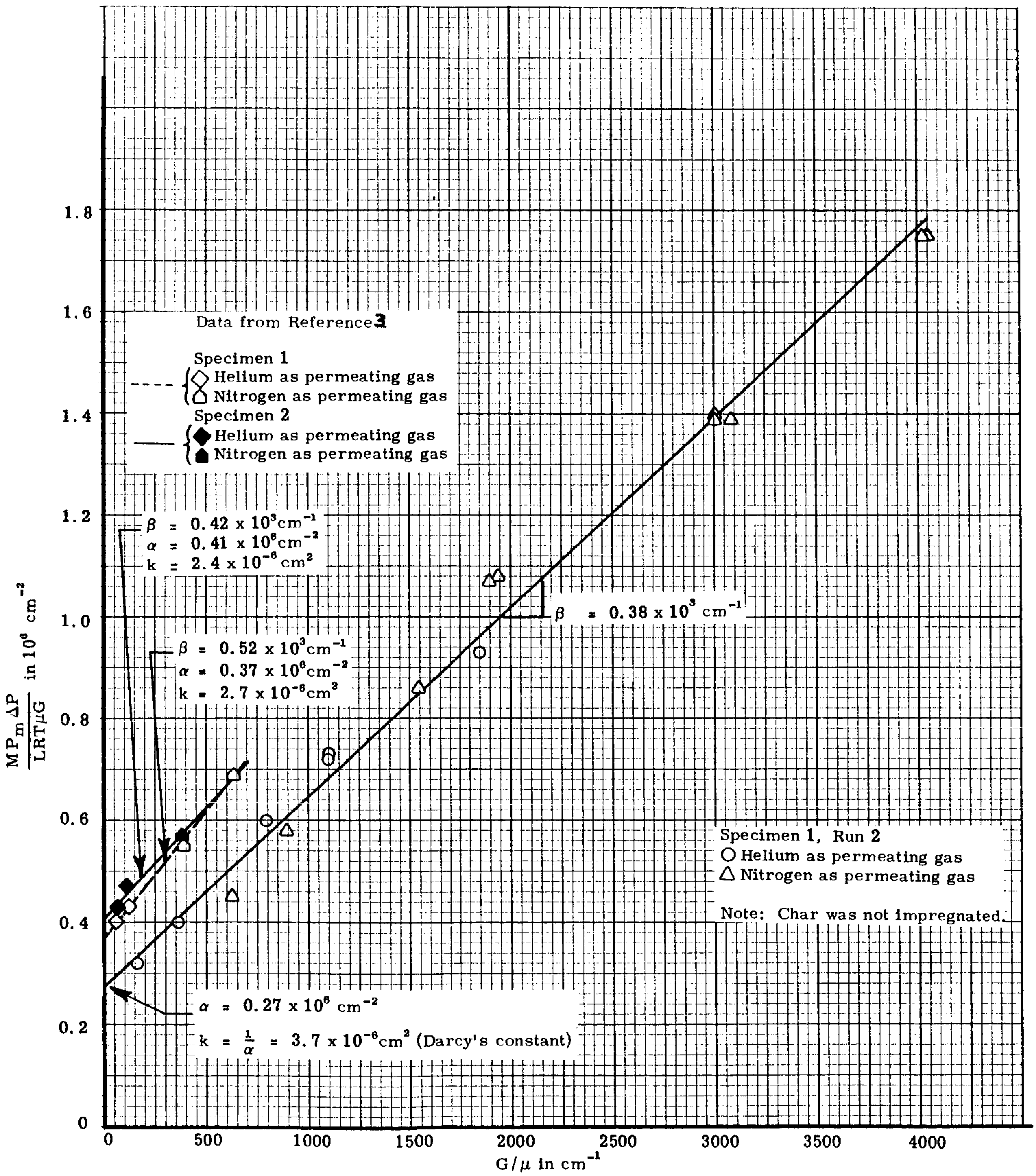


Figure 13. Cornell and Katz plot for low-density phenolic-nylon char (unimpregnated) parallel to the charring direction at room temperature

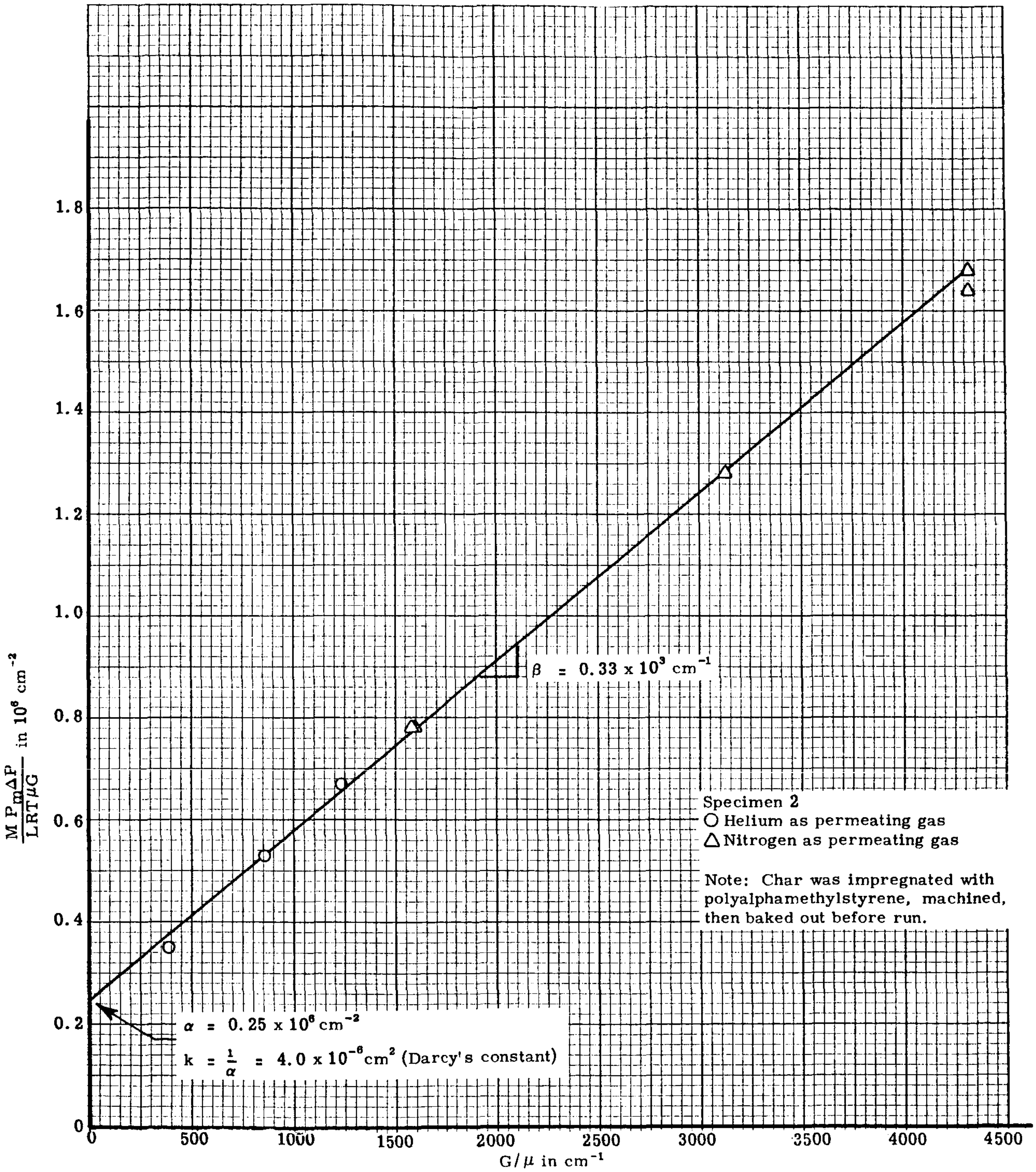
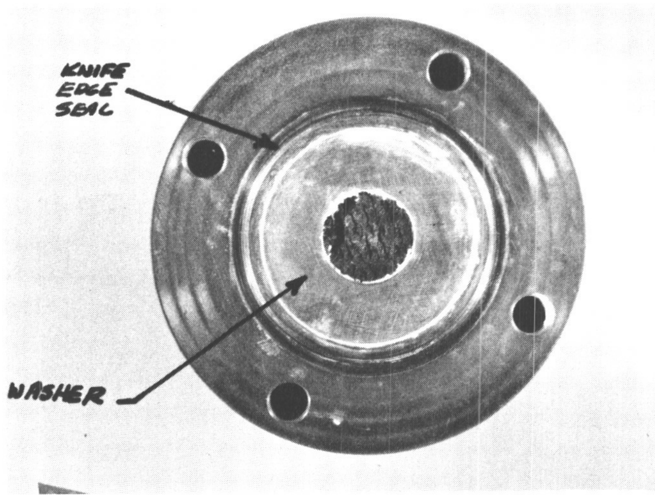
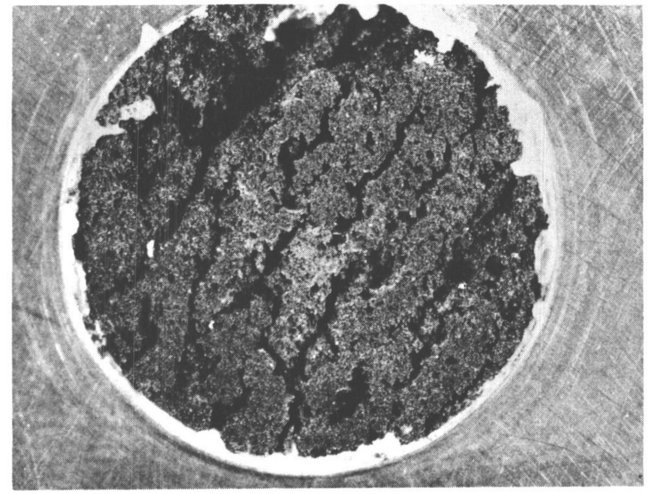


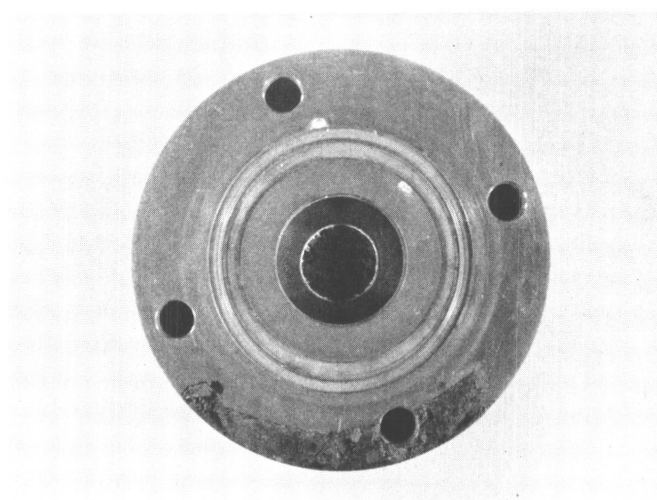
Figure 14. Cornell and Katz plot for low-density phenolic-nylon char parallel to the charring direction at room temperature



Upstream Side of Specimen Mounted in Sauereisen Cement



Expanded View of Upstream Side of Specimen



Downstream Side of Housing Showing Specimen and Support Washer

Figure 15. Pictures of phenolic-nylon char mounted in permeability specimen housing

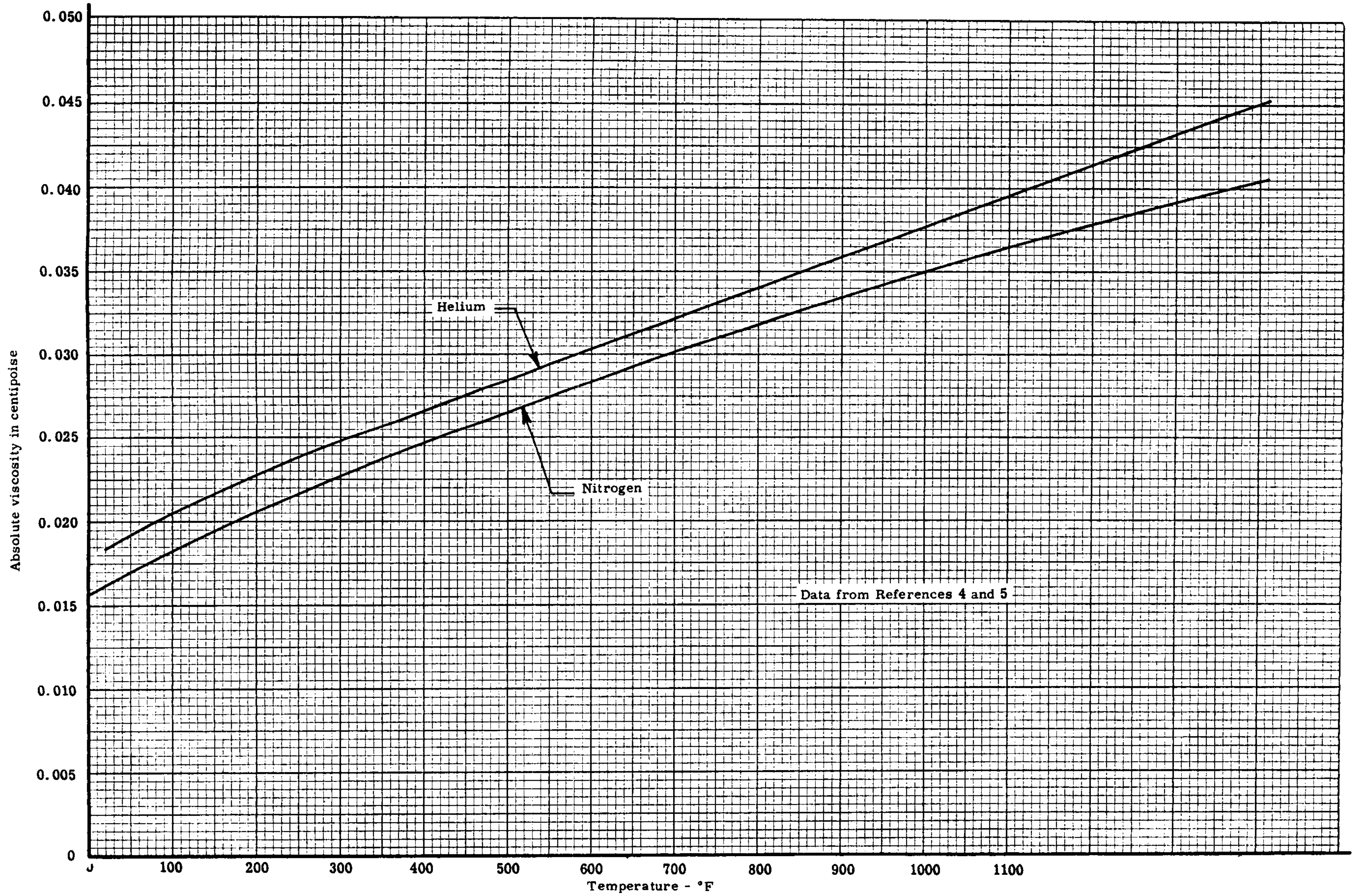


Figure 16. The viscosities of helium and nitrogen

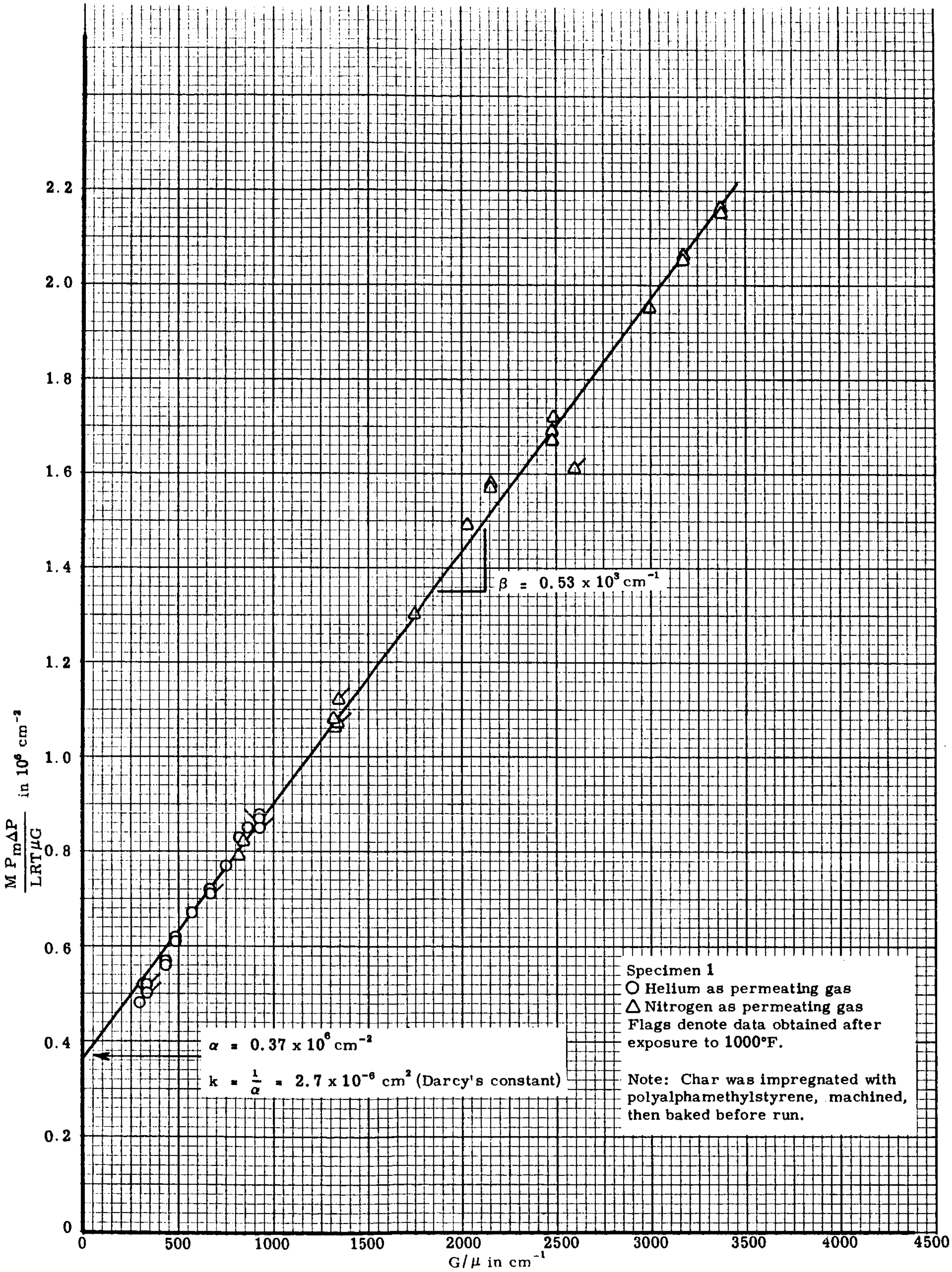


Figure 17. Cornell and Katz plot for low-density phenolic-nylon char perpendicular to the charring direction at room temperature

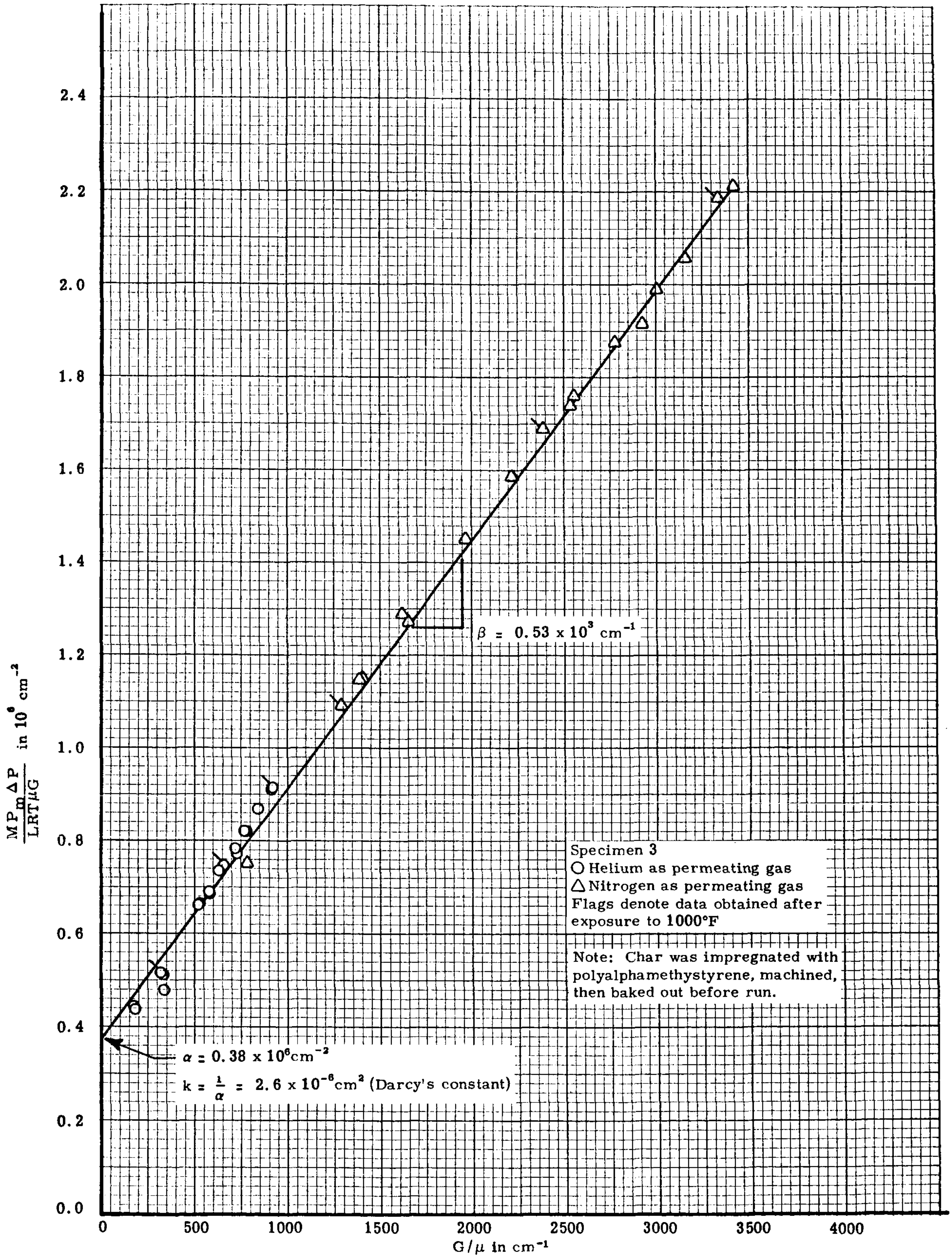
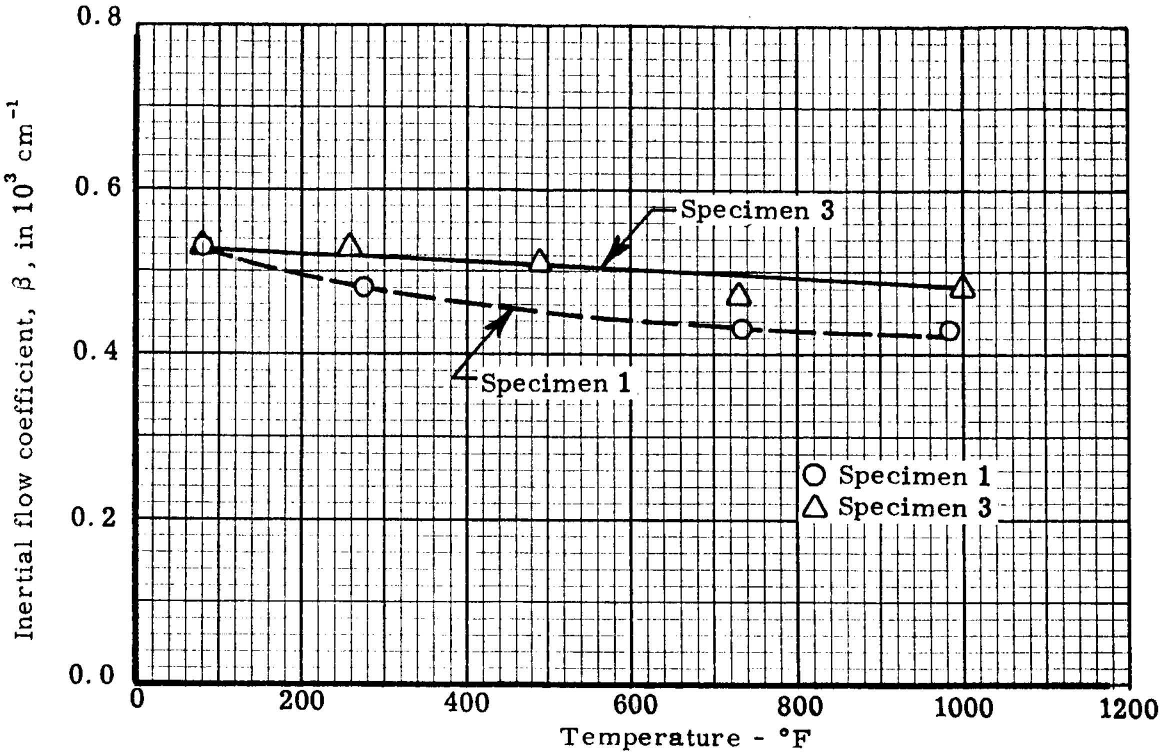


Figure 18. Cornell and Katz plot for low-density phenolic-nylon char perpendicular to the charring direction at room temperature



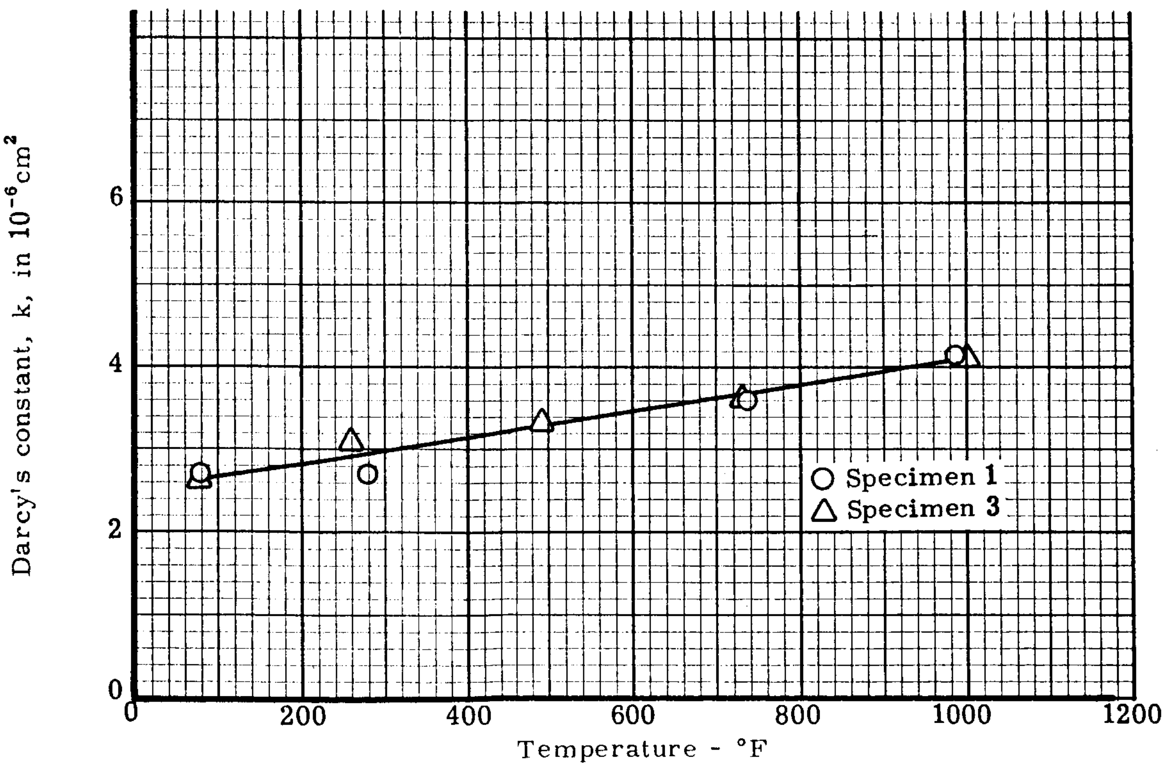


Figure 19. Permeability coefficients as functions of temperature for low-density phenolic-nylon char perpendicular to the charring direction

Table 1

The Permeability of Low-Density Epoxy in the Axial Direction at Room Temperature

Specimen 1
Specimen Area - 5.068 cm^2
Specimen Thickness, L, - 1.275 cm
Specimen Weight - 3.1337 gm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Wet Test Meter Temperature (°F)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
6:30	Nitrogen	29.03	4.0	0.1	31.1	68.0	66	47.8	86.7
	Nitrogen	29.03	8.7	0.1	33.5	68.0	142	52.4	150.3
	Nitrogen	29.03	13.6	0.3	36.1	68.0	233	54.2	304.0
	Nitrogen	29.03	19.2	0.6	39.2	67.5	337	57.0	439.7
	Nitrogen	29.03	24.1	0.9	41.9	67.5	425	60.8	554.5
	Nitrogen	29.03	29.5	1.3	45.0	67.3	524	64.6	685.0
	Nitrogen	29.03	29.8	1.2	45.1	67.3	528	65.2	688.9
7:00	Nitrogen	29.03	29.5	1.2	45.0	-	528	64.2	688.9
9:40	Helium	29.27	3.7	0.1	31.2	70	53	49.2	8.8
9:55	Helium	29.27	8.9	0.1	33.4	70	142	47.8	23.5
10:00	Helium	29.27	14.3	0.1	36.5	70	246	48.0	40.6
10:05	Helium	29.27	19.9	0.2	34.4	69.7	360	49.2	59.4
10:07	Helium	29.27	25.5	0.3	42.3	69.5	479	51.0	79.1
10:10	Helium	29.27	29.5	0.3	44.3	-	585	50.8	96.6
10:13	Helium	29.27	30.2	0.3	44.7	-	602	50.8	99.4
10:15	Helium	29.27	30.1	0.3	44.7	-	602	50.8	99.4
10:17	Helium	29.27	5.1	0.1	31.9	69.4	75	48.8	12.4
10:20	Helium	29.27	10.8	0.8	34.7	69.3	178	47.6	29.4
10:30	Helium	29.28							
1:05	Helium	29.28	26.7	0.3	42.9	68.5	498	52.2	82.2

1. $G = \frac{Q_{STP} \rho_{STP}}{A}$

2. Silastic used as sealant.

Table 2

The Permeability of Low-Density Epoxy in the Axial Direction at Room Temperature

Specimen 2
Specimen Area - 5.064 cm^2
Specimen Thickness, L, - 1.276 cm
Specimen Weight - 3.100 gm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Wet Test Meter Temperature (°F)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
4:49	Nitrogen		4.9	0.1	31.8	71.5	92	43.4	120.4
5:53	Nitrogen	29.27	15.1	0.5	37.3	71.5	294	48.8	383.5
5:15	Nitrogen	29.27	25.6	1.2	43.8	71.3	510	55.4	665.2
5:17	Nitrogen	29.27	30.3	1.6	46.0	-	609	58.4	794.3
8:49	Nitrogen	29.27	7.3	0.1	33.2	71.3	135	45.8	176.1
	Nitrogen	29.27	20.2	0.7	40.3	71.2	408	51.0	532.1
	Nitrogen	29.27	24.4	1.1	42.7	71.0	487	54.6	635.2
	Nitrogen	29.27	30.4	1.6	46.3	-	605	59.4	789.1
	Nitrogen	29.27	10.2	0.2	34.8	71.0	198	45.8	258.2
8:57		29.42							
10:13	Helium	29.42	5.0	0.1	32.0	70.6	86	41.8	14.2
	Helium	29.42	8.7	0.1	34.4	70.6	162	41.8	26.7
	Helium	29.42	12.5	0.1	35.8	70.6	243	41.8	40.1
	Helium	29.42	15.3	0.1	37.2	70.5	311	41.6	51.3
	Helium	29.42	20.0	0.2	39.6	70.5	419	42.8	69.2
	Helium	29.42	25.1	0.3	42.3	70.5	544	44.4	89.8
	Helium	29.42	30.1	0.4	44.9	-	680	45.0	112.2
	Helium	29.42	30.3	0.4	45.0	-	692	44.8	114.2

1. $G = \frac{Q_{STP} \rho_{STP}}{A}$

2. Silastic used as sealant.

Table 3

The Permeability of Low-Density Epoxy in the Axial Direction at Room Temperature

Specimen 4
Specimen Area - 5.075 cm^2
Specimen Thickness, L, - 1.275 cm
Specimen Weight - 3.0746 gm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Wet Test Meter Temperature (°F)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
5:04	Helium	29.52	Began Purge						
5:49	Helium	29.52							
6:05	Helium	29.52	5.1	0.1	32.1	68.0	80.1	45.8	13.2
6:10	Helium	29.52	4.7	0.1	31.9	68.0	75.3	45.0	12.4
6:50	Helium	29.52	10.5	0.1	34.8	67.6	185.2	44.8	30.6
7:00	Helium	29.52	10.3	0.1	34.8	67.5	179.5	45.2	29.6
7:02	Helium	29.52	10.2	0.1	34.7	67.5	177.5	45.4	29.3
7:52	Helium	29.52	14.9	0.1	37.1	66.8	270.1	44.6	44.6
7:55	Helium	29.52	14.3	0.1	36.8	66.8	272.1	43.8	44.9
8:05	Helium	29.52	20.3	0.2	39.9	66.8	384.5	48.0	63.4
8:08	Helium	29.52	20.3	0.2	39.9	66.8	380.9	48.4	62.9
8:12	Helium	29.52	19.4	0.2	39.4	66.8	380.9	45.6	62.9
8:25	Helium	29.52	25.1	0.2	42.3	-	506.7	47.8	83.6
8:28	Helium	29.52	25.1	0.2	42.3	-	506.7	47.6	83.6
8:34	Helium	29.52	25.1	0.2	42.3	-	504.2	47.8	83.2
8:40	Helium	29.52	30.1	0.3	44.9	-	621.7	49.4	102.6
8:43	Helium	29.52	30.0	0.3	44.9	-	621.7	49.4	102.6
8:48	Helium	29.52	30.0	0.4	44.9	-	621.7	49.2	102.6
8:55	Nitrogen	29.54	Began Purge						

Table 3 - continued

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Wet Test Meter Temperature (°F)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
9:35	Nitrogen	29.54	5.2	0.1	32.2	67.2	88.3	48.4	115.0
9:40	Nitrogen	29.54	5.2	0.1	32.2	67.2	87.5	48.6	113.9
9:44	Nitrogen	29.54	5.1	0.1	32.2	67.2	86.9	48.4	113.1
10:00	Nitrogen	29.54	10.3	0.2	34.9	67.1	180.7	51.0	235.3
10:04	Nitrogen	29.54	10.3	0.2	34.9	67.1	177.8	51.6	231.5
10:07	Nitrogen	29.54	10.2	0.2	34.9	67.0	180.7	50.6	235.3
10:15	Nitrogen	29.54	15.3	0.4	37.6	66.8	271.3	54.4	353.2
10:20	Nitrogen	29.54	15.1	0.4	37.5	66.8	271.3	53.4	353.2
10:24	Nitrogen	29.54	15.1	0.4	37.5	66.8	273.3	53.0	355.8
10:35	Nitrogen	29.54	20.4	0.7	40.4	66.8	369.0	57.2	480.4
10:39	Nitrogen	29.54	20.4	0.7	40.4	66.6	376.3	56.0	489.9
10:43	Nitrogen	29.54	20.4	0.7	40.4	66.5	369.0	57.2	480.4
10:50	Nitrogen	29.54	25.4	1.0	43.2	66.2	465.8	60.2	606.5
10:53	Nitrogen	29.54	25.4	1.0	43.3	66.2	471.8	59.6	614.3
10:55	Nitrogen	29.54	25.4	1.0	43.2	66.1	465.8	60.4	606.5
11:00	Nitrogen	29.54	30.1	1.4	45.9	-	573.3	61.8	746.4
11:05	Nitrogen	29.54	30.1	1.4	46.0	-	573.3	61.8	746.4
11:10	Nitrogen	29.54	30.0	1.4	45.9	-	568.3	62.2	739.9
11:30	Nitrogen	29.56							

Table 3 - continued

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Wet Test Meter Temperature (°F)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
8:27	Helium	29.43	Began Purge						
	Helium	29.43	14.9	0.1	37.0	67.4	280.0	44.8	46.2
	Helium	29.43	14.9	0.1	37.0	67.3	279.0	45.0	46.0
	Helium	29.43	19.8	0.2	39.5	67.1	388.0	46.0	64.0
	Helium	29.43	19.8	0.2	39.5	67.0	388.0	45.8	64.0
	Helium	29.43	24.8	0.3	42.1	67.0	507.0	46.8	83.7
	Helium	29.43	24.7	0.3	42.0	67.0	501.0	47.0	82.7
	Helium	29.43	30.1	0.3	44.8	-	628.0	48.8	103.6
	Helium	29.43	30.0	0.3	44.8	-	628.0	48.6	103.6

Table 3 - continued

Time	Permeating Gas	Atmospheric Pressure (in. H_2O)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. H_2O)	Downstream Gage Pressure P_1 (in. H_2O)	Mean Specimen Pressure P_m (in. H_2O)	Wet Test Meter Temperature (°F)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
10:42	Helium	400.93	Began Purge						
	Helium	400.93	23.5	0.7	413.4		26.4	45.2	4.4
	Helium	400.93	23.1	0.7	413.2		26.0	45.0	4.3
	Helium	400.93	19.4	0.7	411.2		21.9	44.8	3.7
	Helium	400.93	19.0	0.6	411.0		21.0	45.6	3.8
	Helium	400.93	14.2	0.6	408.7		16.4	43.4	2.7
	Helium	400.93	13.9	0.6	408.5		16.2	43.0	2.7
	Helium	400.93	10.6	0.5	406.8		12.9	41.0	2.1
	Helium	400.93	10.4	0.5	406.7		12.7	41.0	2.1
	Helium	400.93	4.7	0.5	403.8		5.5	42.4	0.9
	Helium	400.93	4.7	0.5	403.8		5.5	42.4	0.9
11:17	Nitrogen	400.93	12.4	0.6	407.7		13.9	44.4	18.1
	Nitrogen	400.93	12.2	0.6	407.6		13.7	44.4	17.4
	Nitrogen	400.93	5.8	0.5	403.8		6.4	44.8	8.3
	Nitrogen	400.93	5.8	0.5	404.3		6.4	45.2	8.3
	Nitrogen	400.93	3.0	0.4	402.9		3.6	41.2	4.7
	Nitrogen	400.93	3.0	0.4	402.9		3.6	41.2	4.7
	Nitrogen	400.93	0.5	0.1	401.3		0.6	44.8	0.6
	Nitrogen	400.93	0.4	0.1	401.2		0.5	44.0	1.6
	Nitrogen	400.93	0.9	0.1	401.5		1.1	43.2	1.4
	Nitrogen	400.93	0.9	0.1	401.4		1.0	44.4	1.3

Table 3 - concluded

Time	Permeating Gas	Atmospheric Pressure (in. H_2O)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. H_2O)	Downstream Gage Pressure P_1 (in. H_2O)	Mean Specimen Pressure P_m (in. H_2O)	Wet Test Meter Temperature (°F)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
1:54	Nitrogen	400.93	0.5	0.1	401.2		0.6	43.2	0.8
	Nitrogen	400.93	0.5	0.1	401.2		0.6	43.2	0.8
	Nitrogen	400.93	0.5	0.1	401.2		0.6	43.2	0.8
	Helium	400.93	0.3	0.1	401.2		0.4	42.6	0.1
	Helium	400.93	0.3	0.1	401.1		0.3	44.0	0.1
	Helium	400.93	1.0	0.1	401.5		1.2	41.6	0.2
	Helium	400.93	1.0	0.1	401.5		1.1	44.0	0.2

1. $G = \frac{Q_{STP} \rho_{STP}}{A}$

2. Silastic used as sealant.

Table 4

The Permeability of Low-Density Phenolic-Nylon Char Parallel to the Charring Direction at Room Temperature

Specimen 1, Run 1
Specimen Area - 1.617 cm^2
Specimen Length - 0.967 cm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F		Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
						Specimen Housing	Gas (T)			
2:00	Nitrogen	29.40								
2:15	Nitrogen	29.40	1.02	0.09	30.00	70	70	317	1.04	1295
2:20	Nitrogen	29.40	2.15	0.12	30.60	70	70	496	1.43	2025
2:25	Nitrogen	29.40	0.14	0.03	29.50	70	70	96	0.46	393
2:33	Nitrogen	29.40	0.58	0.01	29.70	70	70	240	0.77	980
2:40	Nitrogen	29.40	0.95	0.05	29.93	70	70	306	1.00	1249
2:44	Nitrogen	29.40	1.20	0.07	30.07	70	70	357	1.09	1458
2:47	Nitrogen	29.40	1.60	0.10	30.30	70	70	430	1.21	1758

1. $G = \frac{Q_{STP} \rho_{STP}}{A}$

2. Silastic used as sealant.
3. This specimen was made from unimpregnated char.

Table 5

The Permeability of Low-Density Phenolic-Nylon Char Parallel to the Charring Direction at Room Temperature

Specimen 1, Run 2
Specimen Area - 1.617 cm^2
Specimen Length - 0.967 cm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F Specimen Housing	Temperature °F Gas (T)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
7:46pm	Helium	29.34	0.36	0.00	29.52	80	80	307	0.32	159
	Helium	29.34	0.98	0.01	29.84	80	80	686	0.40	355
	Helium	29.34	0.98	0.01	29.84	80	80	686	0.40	355
	Helium	29.34	3.19	0.02	30.96	80	80	1540	0.60	796
	Helium	29.34	3.19	0.02	30.96	80	80	1540	0.60	796
	Helium	29.34	5.11	0.04	31.94	80	80	2130	0.72	1098
	Helium	29.34	5.17	0.04	31.97	80	80	2130	0.73	1098
8:02pm	Nitrogen	29.34	0.22	0.00	29.45	80	80	153	0.45	623
	Nitrogen	29.34	0.41	0.00	29.55	80	80	220	0.58	899
	Nitrogen	29.34	1.03	0.01	29.87	80	80	378	0.86	1545
	Nitrogen	29.34	1.03	0.01	29.87	80	80	378	0.86	1545
	Nitrogen	29.34	3.14	0.03	30.94	80	80	735	1.40	3000
	Nitrogen	29.34	3.13	0.03	30.94	80	80	735	1.39	3000
	Nitrogen	29.34	5.12	0.05	31.95	80	80	984	1.75	4015
8:17pm	Nitrogen	29.34	5.11	0.05	31.95	80	80	984	1.75	4015
9:00am	Nitrogen	29.36	1.61	0.10	30.27	80	80	478	1.08	1947
	Nitrogen	29.36	1.61	0.10	30.27	80	80	478	1.08	1947
	Nitrogen	29.36	3.20	0.04	31.00	80	80	753	1.39	3080
	Nitrogen	29.36	5.15	0.05	31.99	80	80	992	1.75	4050
	Nitrogen	29.36	1.55	0.10	30.24	80	80	473	1.07	1890
	Helium	39.36	10.29	0.10	34.61	80	80	3560	0.93	1845

1. $G = \frac{Q_{STP} \rho_{STP}}{A}$

2. Silastic used as sealant.
3. This specimen was made from unimpregnated char.

Table 6

The Permeability of Low-Density Phenolic-Nylon Char Parallel to the Charring Direction

Specimen 2
Specimen Area - 1.972 cm^2
Specimen Length - 0.983 cm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F		Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
						Specimen Housing	Gas (T)			
9:12	Helium	29.31	0.98	0.01	29.81	85	85	926	0.35	393
	Helium	29.31	0.98	0.01	29.81	85	85	926	0.35	393
	Helium	29.31	3.07	0.05	30.90	85	85	2015	0.53	854
	Helium	29.31	3.07	0.05	30.90	85	85	2015	0.53	854
	Helium	29.31	5.43	0.10	32.13	85	85	2910	0.67	1232
	Helium	29.31	5.42	0.10	32.12	85	85	2910	0.67	1232
9:24	Nitrogen	29.31	0.99	0.01	29.82	85	85	475	0.78	1590
	Nitrogen	29.31	0.98	0.01	29.81	85	85	471	0.78	1578
	Nitrogen	29.31	3.09	0.05	30.91	85	85	934	1.28	3125
	Nitrogen	29.31	3.09	0.05	30.91	85	85	934	1.28	3125
	Nitrogen	29.31	5.28	0.12	32.07	85	85	1290	1.66	4320
9:37	Nitrogen	29.31	5.26	0.12	32.07	85	85	1290	1.64	4320

1. $G = \frac{Q_{STP} \rho_{STP}}{A}$

2. Sauereisen cement used as sealant.
3. This specimen was impregnated and baked out.

Table 7

The Permeability of Low-Density Phenolic-Nylon Char Perpendicular to the Charring Direction

Specimen 1
Specimen Area - 1.964 cm^2
Specimen Length - 0.944 cm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F Specimen Housing	Temperature °F Gas (T)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3/sec)	(1) $\frac{MP_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
1:55	Helium	29.51	1.06	0.02	30.06	77	77	726	0.52	309
2:58	Helium	29.51	0.94	0.01	29.99	77	77	693	0.48	295
	Helium	29.51	1.59	0.03	30.34	77	77	1008	0.56	429
	Helium	29.51	1.61	0.03	30.35	75	75	1008	0.57	429
	Helium	29.51	1.96	0.04	30.53	75	75	1130	0.62	481
	Helium	29.51	1.90	0.04	30.50	75	75	1121	0.61	478
	Helium	29.51	2.45	0.05	30.79	75	75	1327	0.67	565
	Helium	29.51	2.45	0.05	30.79	75	75	1327	0.67	565
	Helium	29.51	3.05	0.06	31.10	75	75	1545	0.72	659
	Helium	29.51	3.03	0.06	31.09	75	75	1541	0.72	657
	Helium	29.51	3.66	0.08	31.42	75	75	1758	0.77	749
	Helium	29.51	3.65	0.08	31.41	75	75	1758	0.77	749
	Helium	29.51	4.25	0.10	31.74	75	75	1915	0.83	816
	Helium	29.51	4.25	0.10	31.74	75	75	1914	0.83	815
	Helium	29.51	4.53	0.12	31.90	75	75	2014	0.85	858
	Helium	29.51	4.52	0.12	31.89	75	75	2014	0.85	858
	Helium	29.51	5.04	0.14	32.17	75	75	2167	0.88	923
	Helium	29.51	5.02	0.13	32.15	75	75	2164	0.88	922
3:05	Nitrogen	29.45	0.52	0.01	29.72	73	73	251	0.82	843
	Nitrogen	29.45	0.49	0.00	29.70	73	73	243	0.79	817
	Nitrogen	29.45	1.04	0.02	29.99	73	73	394	1.06	1324
	Nitrogen	29.45	1.05	0.02	30.00	73	73	392	1.08	1317
	Nitrogen	29.45	1.67	0.03	30.32	73	73	520	1.30	1747
	Nitrogen	29.45	1.67	0.03	30.32	73	73	520	1.30	1747
	Nitrogen	29.45	2.19	0.03	30.58	73	73	602	1.49	2023
	Nitrogen	29.45	2.19	0.03	30.58	73	73	602	1.49	2023
	Nitrogen	29.45	2.46	0.05	30.73	74	74	640	1.58	2150
	Nitrogen	29.45	2.44	0.04	30.71	74	74	640	1.57	2150
	Nitrogen	29.45	3.07	0.06	31.05	76	76	742	1.72	2493
	Nitrogen	29.45	3.07	0.04	31.03	76	76	742	1.72	2493

Table 7 - continued

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F Specimen Housing	Temperature °F Gas (T)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3/sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
	Nitrogen	29.45	4.11	0.07	31.58	74	74	891	1.95	2994
	Nitrogen	29.45	4.12	0.07	31.58	74	74	891	1.95	2994
	Nitrogen	29.45	4.56	0.08	31.81	75	75	942	2.06	3165
	Nitrogen	29.45	4.54	0.09	31.81	75	75	941	2.05	3162
	Nitrogen	29.45	5.03	0.12	32.09	75	75	1004	2.15	3373
	Nitrogen	29.45	5.05	0.12	32.10	75	75	1004	2.16	3373
9:05	Nitrogen	29.48	3.00	0.07	31.05	75	75	738	1.69	2480
	Nitrogen	29.48	2.97	0.07	31.04	75	75	738	1.67	2480
12:40	Nitrogen	29.46	3.15	0.05	31.09	274	274	618	1.21	1642
	Nitrogen	29.46	3.04	0.05	31.03	274	274	613	1.16	1629
	Nitrogen	29.46	1.04	0.03	30.01	282	282	291	0.53	1162
	Nitrogen	29.46	1.03	0.02	30.00	283	280	291	0.53	1154
1:00	Helium	29.46	3.07	0.04	31.04	290	285	1121	0.58	384
	Helium	29.46	3.06	0.04	31.03	296	296	1070	0.58	364
3:00	Nitrogen	29.44	5.16	0.11	32.63	260	260	869	1.51	2341
	Nitrogen	29.44	5.17	0.12	32.63	260	260	869	1.51	2341
Installed new thermocouple for gas temperature measurement.										
7:30	Helium	29.46	3.05	0.05	31.04	732	732	815	0.37	209
	Helium	29.46	3.00	0.05	31.04	735	737	790	0.37	202
	Nitrogen	29.46	1.35	0.04	30.14	741	738	285	0.48	546
	Nitrogen	29.46	1.35	0.04	30.14	742	738	285	0.48	546
	Nitrogen	29.46	3.49	0.10	31.20	738	737	520	0.71	1003
	Nitrogen	29.46	3.48	0.10	31.30	738	737	520	0.71	1003
	Nitrogen	29.46	4.97	0.12	32.06	738	738	647	0.82	1239
	Nitrogen	29.46	4.96	0.12	32.06	740	740	647	0.82	1235
2:15	Nitrogen	29.44	0.97	0.03	29.96	1005	1007	191	0.37	321
	Nitrogen	29.44	0.97	0.03	29.96	1010	1012	191	0.37	321
	Nitrogen	29.44	2.90	0.08	30.97	1017	1015	405	0.53	677
	Nitrogen	29.44	2.91	0.08	30.98	1019	1018	405	0.53	674
	Nitrogen	29.44	5.78	0.12	32.45	987	968	652	0.73	1114
	Nitrogen	29.44	5.78	0.12	32.45	988	971	652	0.73	1114

Table 7 - concluded

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F		Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
						Specimen Housing	Gas (T)			
3:20	Helium	29.40	1.07	0.01	29.95	1002	994	252	0.29	93
	Helium	29.40	1.01	0.01	29.92	1000	992	250	0.28	93
	Helium	29.40	3.01	0.04	30.95	972	990	667	0.31	149
	Helium	29.40	3.01	0.05	30.76	995	1000	664	0.31	148
	Helium	29.40	4.96	0.09	31.57	1010	1008	993	0.36	221
	Helium	29.40	4.90	0.07	31.92	1013	1013	991	0.35	220
8:00	Helium	29.43	1.17	0.03	30.05	83	81	793	0.52	338
	Helium	29.43	1.12	0.02	30.01	83	81	793	0.50	338
	Helium	29.43	3.00	0.05	30.98	81	80	1550	0.71	660
	Helium	29.43	2.97	0.05	30.97	81	80	1549	0.71	660
	Helium	29.43	5.00	0.09	32.02	81	79	2179	0.87	928
	Helium	29.43	4.90	0.08	31.96	79	78	2176	0.85	927
8:30	Nitrogen	29.43	1.13	0.03	30.03	78	78	401	1.12	1345
	Nitrogen	29.43	1.08	0.03	30.00	78	78	401	1.07	1345
	Nitrogen	29.43	3.02	0.09	31.03	78	78	775	1.61	2599
	Nitrogen	29.43	3.04	0.09	31.04	78	78	775	1.61	2599
8:45	Helium	29.43	0.64	0.02	29.77	78	78	458	0.49	194

1. $G = \frac{Q_{STP} \rho_{STP}}{A}$

2. Sauereisen cement used as sealant.
3. This specimen was impregnated and baked out.

Table 8

The Permeability of Low-Density Phenolic-Nylon Char Perpendicular to the Charring Direction

Specimen 3
Specimen Area - 1.978 cm^2
Specimen Length - 0.932 cm

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F Specimen Housing	Temperature °F Gas (T)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
9:50	Nitrogen	29.39	1.19	0.02	30.01	70	70	423	1.15	1412
	Nitrogen	29.39	1.17	0.02	30.00	70	70	417	1.15	1393
	Nitrogen	29.39	3.21	0.05	31.05	70	70	772	1.76	2560
	Nitrogen	29.39	3.13	0.04	31.00	70	70	762	1.74	2540
	Nitrogen	29.39	5.17	0.06	32.04	70	70	1025	2.21	3420
	Nitrogen	29.39	5.17	0.08	32.06	70	70	1025	2.21	3420
	Helium	29.39	1.12	0.02	29.97	70	70	792	0.51	335
	Helium	29.39	1.02	0.02	29.92	70	70	772	0.48	326
	Helium	29.39	2.93	0.05	30.91	70	70	1495	0.73	632
	Helium	29.39	2.92	0.04	30.89	70	70	1495	0.73	632
	Helium	29.39	5.07	0.08	32.01	70	70	2150	0.91	909
10:14	Helium	29.39	5.06	0.07	31.99	70	70	2150	0.91	909
2:17	Helium	29.35	1.45	0.04	30.12	70	70	949	0.56	401
	Helium	29.35	1.37	0.04	30.08	70	70	897	0.56	379
	Helium	29.35	2.23	0.05	30.52	70	70	1244	0.66	526
	Helium	29.35	2.20	0.04	30.49	70	70	1237	0.66	523
	Helium	29.35	0.52	0.02	29.63	70	70	425	0.44	180
	Helium	29.35	0.51	0.02	29.63	70	70	415	0.44	175
	Helium	29.35	2.53	0.03	30.65	70	70	1371	0.69	579
	Helium	29.35	2.54	0.04	30.66	70	70	1371	0.69	579
	Helium	29.35	4.54	0.06	31.68	70	70	2004	0.87	847
	Helium	29.35	4.55	0.07	31.70	70	70	2004	0.87	847
	Helium	29.35	3.96	0.06	31.39	70	70	1838	0.82	777
	Helium	29.35	3.95	0.07	31.40	70	70	1827	0.82	772
	Helium	29.35	3.58	0.05	31.19	70	70	1725	0.77	729
	Helium	29.35	3.56	0.06	31.19	70	70	1718	0.78	726

Table 8 - continued

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F Specimen Housing	Temperature °F Gas (T)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT\mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
2:51	Nitrogen	29.33	0.43	0.02	29.57	70	70	233	0.75	778
	Nitrogen	29.33	1.53	0.03	30.13	70	70	494	1.27	1650
	Nitrogen	29.33	1.52	0.04	30.13	70	70	486	1.29	1623
	Nitrogen	29.33	2.06	0.06	30.42	70	70	590	1.45	1971
	Nitrogen	29.33	2.05	0.06	30.42	70	70	589	1.45	1967
	Nitrogen	29.33	2.52	0.07	30.66	70	70	665	1.59	2221
	Nitrogen	29.33	2.53	0.07	30.67	70	70	668	1.59	2231
	Nitrogen	29.33	3.65	0.08	31.24	70	70	831	1.87	2776
	Nitrogen	29.33	3.64	0.08	31.23	70	70	831	1.87	2776
	Nitrogen	29.33	4.16	0.07	31.48	70	70	900	1.99	3006
	Nitrogen	29.33	3.99	0.07	31.40	70	70	877	1.95	2929
	Nitrogen	29.33	4.50	0.09	31.67	70	70	946	2.06	3160
3:42	Nitrogen	29.33	4.50	0.09	31.67	70	70	946	2.06	3160
8:18	Nitrogen	29.35	0.97	0.01	29.85	261	258	310	0.76	833
	Nitrogen	29.35	0.94	0.01	29.83	261	259	310	0.73	833
	Nitrogen	29.35	2.03	0.02	30.39	258	259	478	1.05	1285
	Nitrogen	29.35	1.88	0.02	30.31	260	260	468	0.99	1258
	Nitrogen	29.35	5.21	0.07	32.03	260	260	875	1.55	2352
	Nitrogen	29.35	5.21	0.07	32.03	260	258	872	1.56	2344
	Nitrogen	29.35	2.95	0.04	30.87	261	257	606	1.22	1629
	Nitrogen	29.35	2.95	0.04	30.87	259	257	606	1.22	1629
	Helium	29.35	0.91	0.01	29.82	259	254	491	0.41	171
	Helium	29.35	0.85	0.01	29.79	260	255	470	0.40	164
	Helium	29.35	3.04	0.03	30.90	261	254	1237	0.56	431
	Helium	29.35	3.02	0.03	30.89	259	253	1246	0.56	434
	Helium	29.35	5.22	0.06	32.02	259	268	1774	0.69	619
9:14	Helium	29.35	5.16	0.06	31.99	260	259	1767	0.69	616
11:15	Helium	29.38	0.96	0.01	29.87	489	490	378	0.36	112
	Helium	29.38	1.03	0.01	29.91	486	486	405	0.36	120
	Helium	29.38	3.03	0.03	30.93	488	485	1002	0.45	296

Table 8 - continued

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F Specimen Housing	Temperature °F Gas (T)	Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm^3 / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
	Helium	29.38	3.02	0.03	30.92	487	493	987	0.45	292
	Helium	29.38	5.06	0.06	31.97	488	488	1433	0.54	423
	Helium	29.38	5.03	0.06	31.96	488	485	1433	0.53	423
12:00	Nitrogen	29.38	1.03	0.01	29.91	486	493	266	0.59	590
	Nitrogen	29.38	1.03	0.01	29.91	484	490	271	0.58	602
	Nitrogen	29.38	3.23	0.04	31.04	483	483	547	0.94	1214
	Nitrogen	29.38	3.27	0.04	31.06	484	484	549	0.94	1219
	Nitrogen	29.38	5.02	0.07	31.96	489	489	723	1.13	1605
	Nitrogen	29.38	5.01	0.07	31.96	489	489	726	1.12	1611
2:00	Nitrogen	29.38	0.97	0.01	29.88	742	739	235	0.43	450
	Nitrogen	29.38	0.98	0.01	29.88	739	739	227	0.45	435
	Nitrogen	29.38	3.09	0.04	30.97	733	727	475	0.71	910
	Nitrogen	29.38	3.08	0.04	30.96	733	727	471	0.71	902
	Nitrogen	29.38	5.18	0.07	32.04	727	723	657	0.89	1258
	Nitrogen	29.38	5.17	0.07	32.04	727	723	657	0.89	1258
2:20	Helium	29.38	0.98	0.01	29.88	732	732	301	0.32	77
	Helium	29.38	0.98	0.01	29.88	732	732	298	0.32	76
	Helium	29.38	3.03	0.03	30.93	733	727	831	0.37	212
	Helium	29.38	3.03	0.03	30.93	733	727	831	0.37	212
	Helium	29.38	4.90	0.06	31.89	735	735	1140	0.45	291
	Helium	29.38	4.89	0.06	31.89	735	735	1140	0.44	291
4:00	Helium	29.38	0.99	0.01	29.89	999	998	257	0.27	57
	Helium	29.38	0.99	0.01	29.89	999	998	257	0.27	57
	Helium	29.38	3.43	0.04	31.14	1004	1004	758	0.33	168
	Helium	29.38	3.42	0.04	31.13	1004	1004	751	0.33	167
	Helium	29.38	5.06	0.05	31.96	1000	1000	1035	0.36	230
	Helium	29.38	5.06	0.05	31.96	1000	1000	1035	0.36	230

Table 8 - concluded

Time	Permeating Gas	Atmospheric Pressure (in. Hg)	Pressure Drop through Specimen $(P_2 - P_1)$ ΔP (in. Hg)	Downstream Gage Pressure P_1 (in. Hg)	Mean Specimen Pressure P_m (in. Hg)	Temperature °F		Volumetric Flow Rate Corrected to Standard Conditions Q_{STP} (cm³ / sec)	(1) $\frac{M P_m \Delta P}{LRT \mu G}$ (in $10^6 cm^{-2}$)	(1) G/μ (cm^{-1})
						Specimen Housing	Gas (T)			
4:25	Nitrogen	29.38	1.04	0.01	29.91	1005	1005	213	0.36	356
	Nitrogen	29.38	1.04	0.01	29.91	1005	1005	213	0.36	356
	Nitrogen	29.38	3.16	0.04	31.00	1004	1004	421	0.58	703
	Nitrogen	29.38	3.16	0.04	31.00	1004	1004	421	0.58	703
	Nitrogen	29.38	5.02	0.08	31.97	1005	1004	567	0.70	947
	Nitrogen	29.38	5.02	0.08	31.97	1005	1005	567	0.70	947
3:10	Nitrogen	29.31	1.03	0.01	29.84	70	70	385	1.09	1286
	Nitrogen	29.31	2.87	0.04	30.79	70	70	714	1.69	2385
	Nitrogen	29.31	5.02	0.07	31.89	70	70	1001	2.19	3343
3:22	Helium	29.31	1.07	0.01	29.86	70	70	752	0.52	318
	Helium	29.31	3.09	0.04	30.90	70	70	1550	0.75	655
	Helium	29.31	5.14	0.06	31.94	70	70	2173	0.92	918

1. $G = \frac{Q_{STP}\,\rho_{STP}}{A}$

2. Sauereisen cement used as sealant.
3. This specimen was impregnated and baked out.